THE DEVELOPMENT OF THE ELECTROCARDIOGRAPH

WITH SOME BIOGRAPHICAL NOTES
ON
PROFESSOR W. EINTHOVEN

1903 — 1952

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INTRODUCTION

This publication is one of a series of monographs dealing with the association of prominent men of science with the Cambridge Instrument Company Ltd. For the most part they will relate the pioneer development of various scientific instruments that have had a marked effect on the progress of scientific achievement or industrial development. It will be seen how frequently the laboratory instrument of the day becomes the industrial tool of the future.

The object of these monographs is to place on record the indebtedness of the instrument makers, and indeed the whole world, to these men of science and to detail the story of the collaboration before the all destroying hand of time blots it from the memory of those who had part in it.

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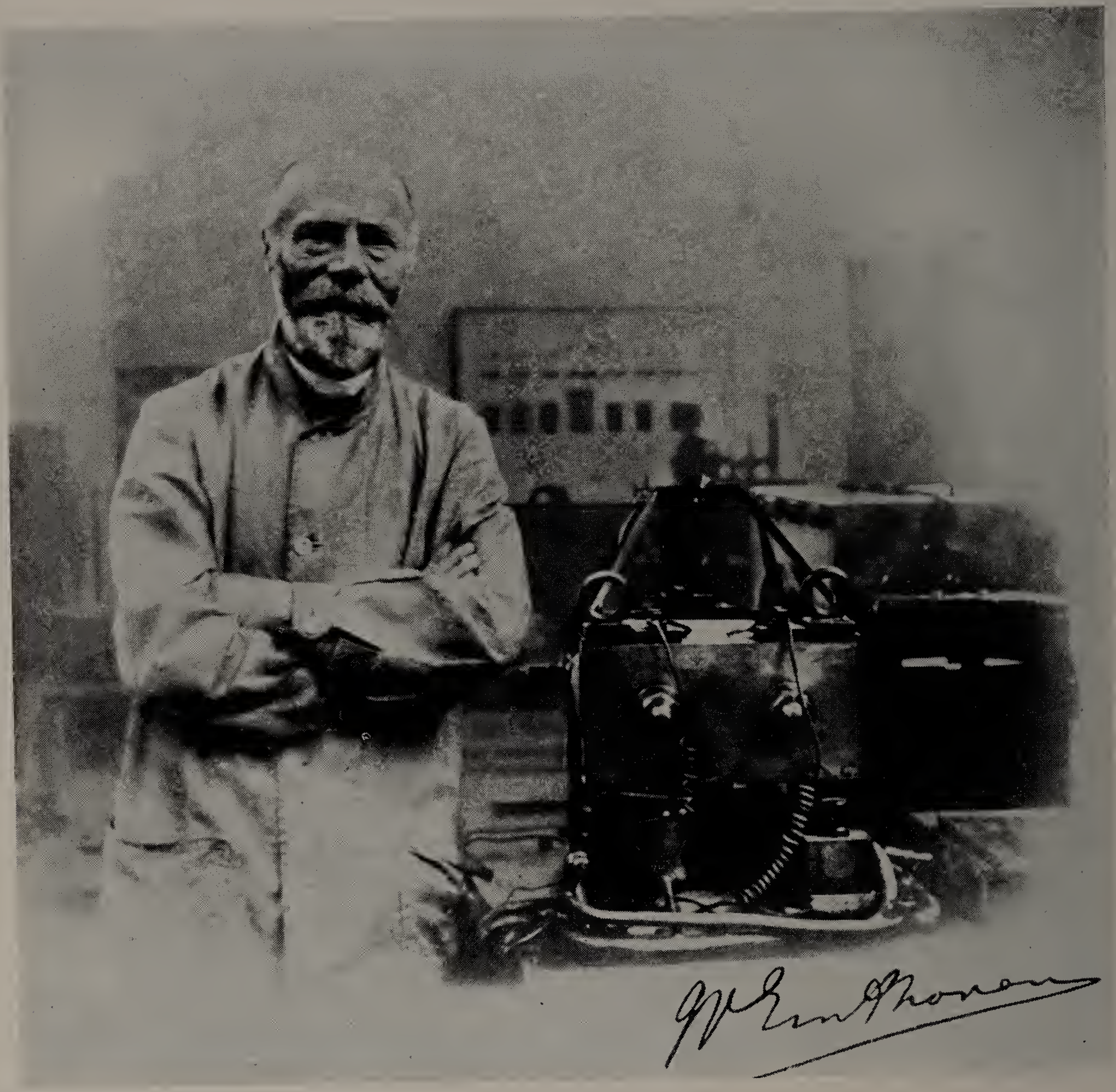

Frontispiece : PROFESSOR WILLEM EINTHOVEN in his laboratory at Leyden University with the original Einthoven String Galvanometer Outfit.

FOREWORD

BY

Sir Alan Drury, C.B.E., M.D., F.R.C.P., F.R.S.

Director : The Lister Institute of Preventive Medicine

It is a pleasure to write a foreword to this monograph on the development of the electrocardiograph.

I had the good fortune to spend some months with Professor Einthoven in his laboratory at Leyden and to be associated with Sir Thomas Lewis for a number of years. The memory is unforgettable. At Leyden one was astounded at the ingenuity of the mechanics and technicians in overcoming the problems which Einthoven posed them. He was not a practical man but insisted that his ideas could be embodied and put into practical form if the proper attempt was made. His work resulted in the building of a string galvanometer of extreme sensitivity. This in itself was a magnificent achievement but in a series of classical papers he indicated the problems in cardiology which could be attacked by the use of the string galvanometer.

Sir Thomas Lewis quickly saw the potentialities of this instrument and in 1912 *began publishing the results of a series of investigations using the Cambridge electrocardiograph. As work progressed, he called for modifications in design which he knew would give him the information he sought. It was the function of others to produce, and this work fell on the Cambridge Scientific Instrument Co. and in degree upon the writer of this publication who became the contact between Sir Thomas and the Company, and, therefore, writes with first hand knowledge of the subject. It is astonishing what Sir Thomas and his department achieved. Within the space of a few years a large number of papers were published dealing with many different aspects of cardiology which not only produced much information of lasting value but also fired workers in other countries to take up this field of work. Many visiting workers from all parts of the world, but chiefly from Great Britain and the United States of America were closely associated with him during this period of intense activity.*

I believe all of them carry lasting memories of the dark and unprepossessing basement room at University College Hospital where the cardiograph "rented" by the Cambridge Company to Sir Thomas Lewis was housed, and where they—working in overcrowded and uncomfortable circumstances—came under the spell of Lewis' galvanic personality.

It is most satisfactory that this interesting and well balanced history should have been written, for it puts on record the large amount of work which was necessary before the efficient and reliable electrocardiograph in common use today could be produced.

I like to think that this monograph is a tribute to Professor Einthoven, Sir Thomas Lewis and Professor Williams who, in their different ways, were largely responsible for the design and exploitation of the string galvanometer which has allowed such quick and outstanding progress to be made in our knowledge of the various clinical disorders of the heart beat.

THE DEVELOPMENT OF THE ELECTROCARDIOGRAPH

BY

S. L. BARRON

At the latter end of the last century the discovery of an electrical potential associated with muscular contraction was investigated by physiologists in connection with the electrical wave accompanying the contraction of the heart musculature. Gotch and Burch and more particularly A. D. Waller in London used a Lippman capillary electrometer and were able to establish a form of electrical curve associated with the contraction of the human heart (1). Waller's work dated from 1887 and a paper was read before the Royal Society in 1888 entitled "On the Electromotive changes connected with the beat of the mammalian heart, and of the Human heart in particular." This paper was published on June 6th 1889 in the Philosophical transactions and printed in the completed volume in 1890. Waller undoubtedly introduced the term electrocardiogram to describe the record of electrical potential associated with the action of the heart and this term has remained in current use. Dr. M. D. Waller (daughter of A. D. Waller) has recalled that electrodes attached to the chest wall were the first to be used but that in an address given by her father at the St. Mary's Hospital Medical School in 1888 illustrations showed a man with his hands immersed in pots containing liquid and of a dog standing with one fore paw and one hind paw in dishes of water in order that the electrocardiograms might be recorded. This apparatus had certain inherent drawbacks, which prompted Prof. Willem Einthoven of Leyden University, working with an exceptional team of designers and technicians, to apply his remarkable facility as a physiologist to the production of a suitable form of recording galvanometer for this purpose. Dr. Berghansius, then working with Einthoven, was largely responsible for putting the theoretical ideas into practical form.

The instrument now known as a "string galvanometer" had been known in theory and principle for some years, and had been applied by Ader for use in cable telegraphy, and described by him in 1897 (2). It consisted of a single metal fibre stretched in a magnetic field provided by a group of permanent magnets placed one upon another and was intended as a quick period system rather than a very sensitive one. Even earlier, in 1892, Ewing had described what was in effect a bifilar galvanometer, containing two conductive fibres bridged across the centre by a small mirror, and the whole inserted in a strong magnetic field. This was used for tracing magnetization curves, and escaped notice as a reflecting mirror galvanometer.

Einthoven started his experiments by the development of a highly sensitive D'Arsonval moving coil galvanometer, and found that the smaller the number of windings on the coil, the greater the normal sensitivity. This led first to a single-turn coil, and then to the stretching of a single fibre in a strong magnetic field. Einthoven was at this time unaware of the work of Ader. The problem which confronted him was to make an instrument of sufficiently high internal resistance, dead beat, with quick period, high sensitivity and stable for accurate calibration. As sensitivity is normally obtained with a sacrifice of period and stability, it was, at that time, a great problem. Using, for theoretical reasons, a fine wire, he attacked first the problem of galvanometer resistance, and discovered a method of chemically plating with silver fine quartz fibres (made by the method devised by C. V. Boys) (9). These were found to be electrically conductive, possessed the desired electrical resistance, and owing to their small mass they had practically no moment of inertia. These fibres were tautly suspended in the poles of a powerful electro-magnet, and the shadow of the fibre or "string" projected by a specially designed microscope system, the movement of the string shadow being photographed on a moving photographic plate.

Einthoven's equipment, when completed, was large and unwieldy; the large electro-magnet was surrounded by a water jacket for cooling, and the string projected by an arc lamp (see frontispiece). It was first described by Einthoven in 1903 in his historic paper "*Ein neues Galvanometer*" (3), which was quickly followed by a paper entitled "*Enregistrement Galvanométrique de l'électrocardiogramme humain et contrôle des résultats obtenus par l'emploi de l'electrométre capillaire en physiologie.*" (4). This was a masterly work comparing the work of Waller using a capillary electrometer, with the use of the new "string" galvanometer. It succeeded in establishing the "string" instrument as highly accurate, and caused the capillary electrometer to become obsolete for this purpose. It is of interest to note the exceptional quality of the first electrocardiograms reproduced in this paper; they have scarcely been surpassed to the present date (Fig. 1). Thus was the true electrocardiogram born, and physiologists all over the world expressed their interest in this novel equipment.

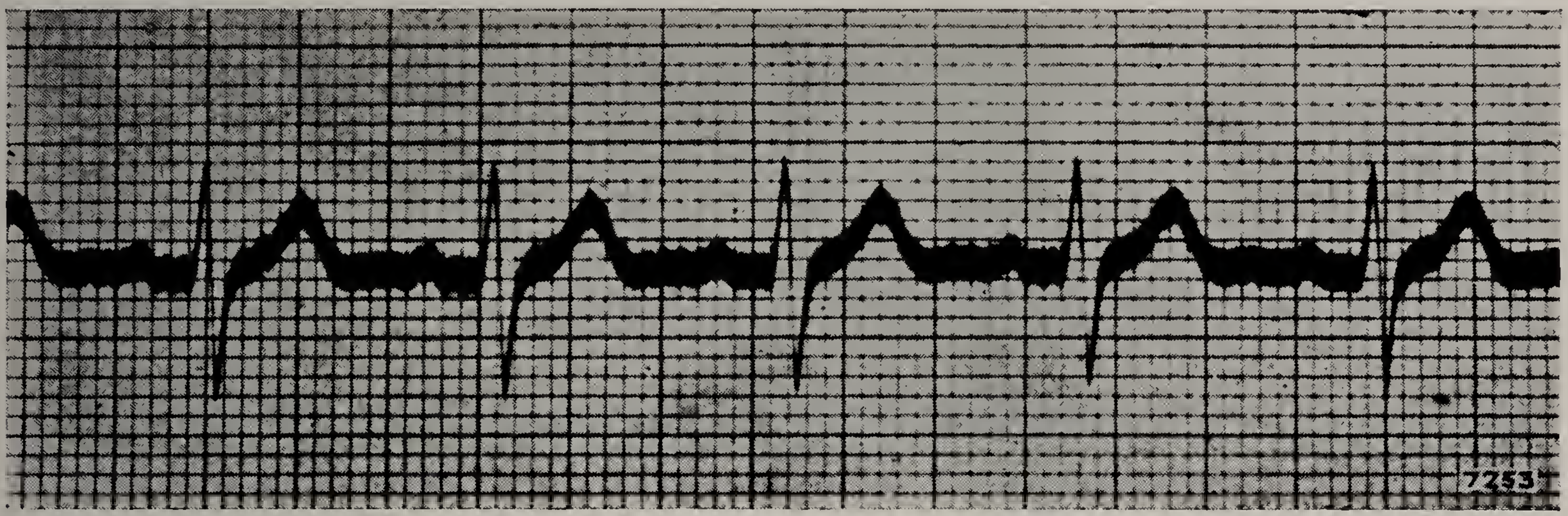

FIG. 1. Early electrocardiogram made by Einthoven on his original outfit.

Einthoven followed up his discovery by a long and painstaking investigation in which he established the forms of connection to the patient, details of the electrodes to be employed, the establishment of sensitivity standards, and the interpretation of the more general changes in heart rhythm as shown by differing types of electrocardiogram (5). This investigation resulted in the Einthoven convention of a sensitivity of 1 cm. deflection for 1 millivolt at 600 diameters magnification, and the three-lead electrocardiogram from Right Arm/Left Arm, Right Arm/Left Leg and Left Arm/Left Leg, named Leads 1, 2 and 3. This convention and usage, together with the nomenclature invented by Einthoven, has remained the standard to the present day, and was only extended by the introduction of chest leads in 1928/30, the Unipolar Chest leads of Wilson in 1934 and the augmented unipolar limb leads of Goldberger in 1942. Einthoven's paper also demonstrated the true nature of the extra systole, and gave examples of many forms of the more common abnormal rhythms. This was followed by a series of classical papers on the subject.

The interest of physiologists was now greatly stimulated, but the only available equipment was that made by Einthoven in his own laboratory. Prof. H. B. Williams of Columbia University in the United States of America visited Einthoven, and afterwards designed and made an instrument in his laboratory for his own use. This was the first instrument to be used on the American continent.

In the meantime Einthoven communicated details of his invention to Horace Darwin (later Sir Horace Darwin, F.R.S.) of the Cambridge Scientific Instrument Company in England, and to Messrs. Edelmann in Germany, with a suggestion that they should design and manufacture, under a royalty agreement, an "electro-cardiograph" that could be marketed. A representative from the Cambridge Company visited Leyden and inspected the equipment, but he found it so large and unwieldy, (it occupied two rooms and took five people to operate it) and so obviously needing radical re-designing, that enthusiasm was lukewarm and progress slow; furthermore it was not until the publication of Einthoven's paper in 1908 that the full significance of the invention, as a diagnostic instrument, became obvious to the medical profession. Edelmann in the meantime made what was almost a copy of the Einthoven instrument, and afterwards introduced many points of new design; at this time an unfortunate difference with Messrs. Edelmann, who had discovered the earlier publications of Ader, caused them to consider void their agreement as to royalties, and co-operation with Einthoven ceased. This occurrence had a great effect on Einthoven; it made him for many years distrust commercial enterprises, particularly those in Germany, and contact with him became difficult. Fortunately the Cambridge Scientific Instrument Company honoured their agreement to the end, and received loyal co-operation, although almost all subsequent communications were subject to secrecy and confidential qualifications until Einthoven himself had published the subject matter.

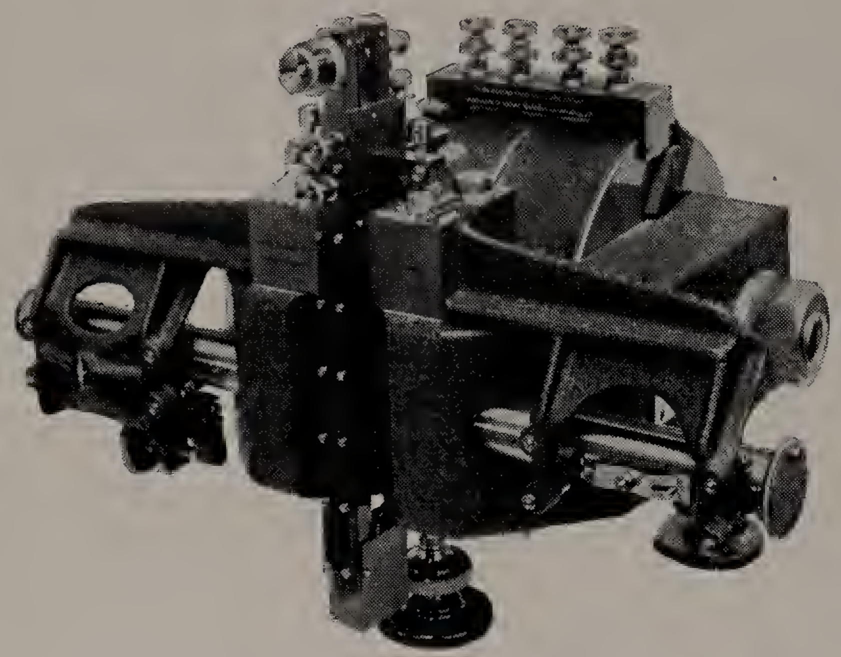

Fig. 2. Einthoven Galvanometer, 1912 model (Cambridge Scientific Instrument Co., Ltd.).

The Cambridge Company proceeded with the design of a String Galvanometer, and produced many features of great interest. The design was carried out by W. D. Duddell, F.R.S., who had then acquired fame by his introduction of the Duddell Oscillograph. He succeeded in reducing the size of the electromagnet by paying great attention to the shape and thus obviating magnetic leakages, and concentrating the magnetic field in the "string" gap; he also commissioned special optical work (made by Zeiss) so that the hole through the magnet poles should be as small as possible. In this way he was able to obtain a magnetic field of 20,000 gauss as against the 22,000 normally obtained with the water-cooled Einthoven instrument. Improvements in the "string" carrier and width of the gap compensated for this slight difference, and the overall performance of the Duddell instrument was at least equal to that of the original albeit only a fraction of the weight and size. Mr. W. D. Duddell was responsible for the suggestion to enclose the delicate "string" in a separate carrier, as he was convinced of the effect of convection currents and draughts on an exposed string. This was a wise precaution, and for many years established the Cambridge galvanometer as the most robust and stable of its kind (Fig. 2). Later developments rendered the enclosed string unnecessary, and the exposed string is now used almost universally. Einthoven fully approved of and first described the Cambridge Galvanometer in 1909, in a paper which also referred to a string galvanometer designed by W. Salomonson of Amsterdam (6). The latter considerably influenced the design of the subsequent Edelmann intrument.

The first complete Cambridge electrocardiograph was completed in 1911, and supplied "on hire" with right to purchase to Dr. Thomas Lewis, and was installed in a basement in University College Hospital, London. Other outfits were quickly completed and supplied to The London Hospital (Sir James Mackenzie), Leeds Royal Infirmary (Dr. Wardrop Griffiths) Dr. McIlwaine (Belfast Royal Infirmary) Dr. Cowan (Glasgow Royal Infirmary) and Dr. Avory Newton, to mention but a few (see Appendix p. 25). The first Cardiographic department to be created was probably that at the London Hospital; the electrocardiograph

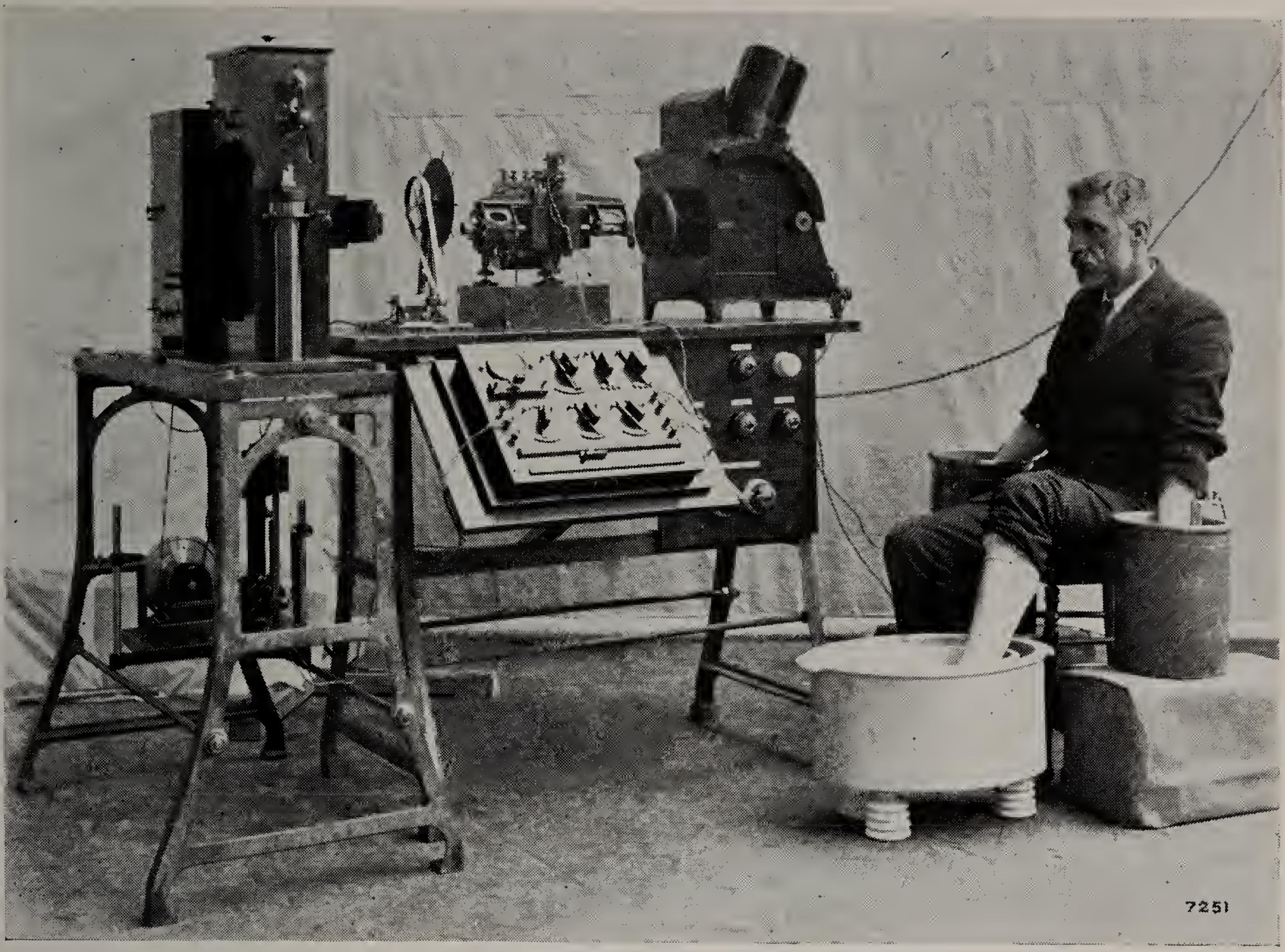

FIG. 3. Original Cambridge complete electrocardiograph as used by Sir Thomas Lewis, F.R.S. (1912.)

was installed early in 1913 and was used by Dr. John Parkinson (afterwards Sir John) who from this date began publishing papers dealing with the electrocardiograph in clinical practice. The outfit installed at University College was used primarily for research purposes. The first catalogue describing the complete outfit was issued early in 1913. (Fig. 3).

On the continent of Europe other manufacturers produced different models. One of the most interesting was made in 1911 by Messrs. E. F. Huth, with the co-operation of Prof. F. Martins and Prof. G. Nicholai of Berlin. It was much smaller and lighter than the Einthoven instrument and did, in fact, provide the basis of a transportable outfit. The electrodes employed were of metal foil enclosed in long flannel stockings which were soaked in saline solution and wrapped around the limbs. The time marker was of novel design and consisted of a tuned reed, projected in the light beam, and kept in vibration by a puff of air generated by the rotation of the camera motor. The outfit could be arranged to record four phenomena simultaneously, *i.e.* pulse and apex beats, heart sounds and the electrocardiogram. Ideologically this outfit was years before its time ; it was portable, vibration free, sensitive, fitted with an automatic developing camera and had only two control knobs, making operation very simple. Unfortunately it had many defects in design and was troublesome in operation ; it never obtained the widespread use that many of its features deserved although early attention to some details might have made it an instrument of first importance throughout the world.

Another interesting outfit was produced by Messrs. Siemens & Halske about 1914. It abandoned the Einthoven Galvanometer and returned to a very light moving coil tautly suspended by two pairs of fine wire filaments, similar to that described by Ewing in 1892. The coil carried a small mirror and the record was made by a reflected light beam. Skin current or zero current compensation was effected by blocking the direct current impulse with a 50 mf. condenser instead of the usually employed potential counter-current device. It is interesting to note that this method of compensation was "rediscovered" about 1930 and is now incorporated in many modern outfits. The Siemens instrument also employed Marey tambours for pulse and apex tracings, but in this case a small mirror was mounted "off centre" on the diaphragm and the record made by a reflected light beam. This method is also now used in many modern outfits. This oscillographic type of apparatus was considerably developed and used on the continent of Europe until it was ultimately replaced by the valve amplified instruments. In France a string galvanometer outfit was produced by Messrs. Boulitte.

By the outbreak of the War in 1914, about thirty-five Cambridge outfits had been supplied, (ten in the U.S.A.) which was quite a good performance, by a small firm, when one has regard for the complexity of the whole outfit at that date. At this time the illuminating system was a large 15-ampere arc lamp, which had an inconvenient habit of flickering at the wrong moments. The electrodes consisted of large earthenware baths containing a zinc electrode, and an inner porous porcelain pot. The inner vessel was filled with a 20 per cent salt solution, and the other with zinc sulphate solution and connection made to a terminal fixed to the zinc plate immersed in the zinc solution. The limbs were immersed in the inner vessel. Einthoven had given much thought and experiment to these electrodes, and they were considered essential for eliminating polarization effects. The inner porous pots were often difficult to obtain and frequently caused a bottleneck in the production of the complete instrument. Later, electrodes in the form of zinc trays each carrying two pads, one saturated in $Zn\ SO_4$, and the other in salt solution, were employed, in which case the palms of the hands and base of the foot were pressed in contact with the salt pads. They were never really satisfactory, but were deemed more suitable for consulting-room work. The earthenware jars were standard until the introduction of direct contact strap-on electrodes in 1928, although, in America, an electrode of German silver foil in a saturated flannel jacket had been used with a degree of success for some years. A specially designed control-board accommodated the lead selector switch, standardizing switch and a skin current compensator. The latter was effected in one of two ways. In the U.S.A., Prof. Williams preferred a method of balancing the skin current by a resistance bridge method, whilst in England the Cambridge Company used a tapped potential slide wire and balanced the skin current by an equal and opposite current from the slide. As is known, the skin current may vary in polarity, and this was allowed for in the American instrument by adding a reversing switch, and in the Cambridge instrument by balancing the slide wire in its centre. In both instruments standardization was effected by inserting 1 millivolt in the patient circuit, and adjusting the fibre tension to procure a deflection of 1 cm. on the camera scale. The American instrument used a continuous paper or film camera, whilst the British instrument standardized a falling plate camera that was exposed in three sections so that the three standard records could be taken side by side. This was considered by many to be more convenient for examination and analysis; it enabled any number of contact prints to be made, and this familiar three-lead electrocardiogram is still in use today. Later work involving exercise tests and the introduction of multiple lead electrocardiograms have swung the pendulum in favour of continuous records, and such cameras are now being made in increasing numbers.

It may now be opportune to deal with some of the difficulties experienced in the design of the early instruments. Perhaps the most important was the temperature effect on the fibre. The powerful electromagnets were bound to generate heat, which communicated itself to the fibre system. As the co-efficient of expansion of the metal fibre mount and the quartz fibre itself were greatly different, the fibre became more taut as the temperature rose, and the sensitivity rapidly changed. It was for this reason that Einthoven had introduced his heavy, continuous flow, water jacket. Duddell obviated much of this effect by placing the magnet coils at the back of the heavy iron magnet forgings, so that a large mass of metal must be warmed before the temperature change reached the fibre system. He also arranged for more effective windings and heat dissipation. These galvanometers retained a constant sensitivity for considerable periods, but in experimental work extending over a long time re-calibration was sometimes necessary. Edelmann began to use metallic fibres made by the Woolaston process, in which the coefficient of expansion of the fibre and the carrier were more nearly equal, but the Woolaston wire was very difficult to treat and very brittle after processing. Convection currents and draughts causing the fibre to wander were obviated in the instrument designed by the Cambridge Company by enclosing the string in an airtight carrier, the image being projected through two small windows covered with cover-plate glasses or mica slips.

One of the most exasperating causes of trouble was due to the disappearance of the string image in the optical field. When it is realized how short was the focus of the objectives and how fine the string (0.003 mm.) it is not difficult to imagine how easily the focussing adjustment could be altered to cause the image to disappear. There also existed an adjustment to displace the string in relation to the optical system, and this adjustment was held in position by a spring. Changes in the spring tension and a very slight displacement of the string carrier (of the order of 0.1 mm.) was sufficient to displace the string entirely out of the field of view. To find it again, and to re-centre it, was an operation that required considerable practice and patience, and frequent were the calls, often to travel many miles, only to find that the string had become displaced (often due to excessive loosening on the part of the operator), and that in an endeavour to re-locate it the physician had made confusion worse confounded by disarranging almost every adjustment of which the galvanometer and optical system were capable. Experienced technicians could perform the task systematically, in a matter of minutes, whilst the distracted physician often spent fruitless hours. Whilst mentioning "strings", it was a common conception that these were very frail and liable to breakage: this was not the case unless they were exposed to excessive draught. It is a continual source of wonderment that a moving system of such delicacy could be handled as they were, and it is a great tribute to Einthoven's genius that he should ever have conceived that the apparatus could have been made as a commercial proposition for general use by physicians outside of a fully equipped laboratory.

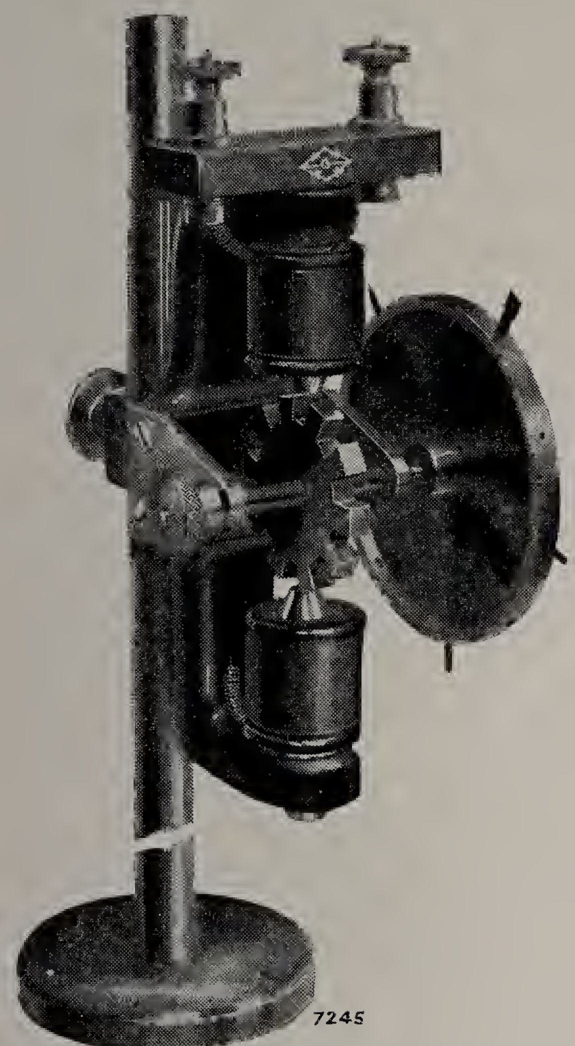

Fig. 4. Rayleigh rotary time motor. (1915).

Heat generated by the arc lamp was also a source of trouble, particularly since the microscope focused the beam on to the string and concentrated heat at this point. To reduce this effect, a water bath with two windows was placed between the arc lamp and the microscope, thus absorbing the heat rays before entering the galvanometer optical system. This water bath frequently grew fungoid growths and other organisms that absorbed much of the illuminating power of the lamp.

Alternating current was not then in general use, and defects caused by A.C. leakage were not common ; electro-static charges, were, however, troublesome, and in many cases the early instruments were completely enclosed in Faraday cages.

For providing a time base for his records Einthoven first used a bicycle wheel with specially spaced spokes, which was rotated at a definite speed and so placed that the spokes cut the optical projection beam each 1/25 second, thus ruling a line on the resulting photographic record. All Einthoven's early records were taken with a time base of 1 mm. for 1/25 second. Time markers for the early commercially constructed instruments were tuned vibrating reeds of the tetanus spring type, kept in operation by an electrical pulse through a contact on the spring; they marked each 1/50th second, and were arranged to rule across the record or along the fringe. Later, synchronous motors of the Rayleigh type, operated by a 50 cycle tuning fork, came into general use; they marked each 1/25th second, with a thicker line each

1/5th second (Fig. 4). This marking has remained standard, although the time motors are now less complicated, and are automatic in operation. On occasions it took literally hours to get the Rayleigh motors to run satisfactorily, since they had to be started manually by spinning the wheel steadily at exactly the synchronous speed, a technique not easily acquired, but when once mastered made operation easy. The writer remembers many occasions being called by irate physicians who had spent fruitless hours, only to arrive and give the wheel one spin to set it going merrily. These wheels could also be started at exactly double speed and this gave rise to considerable difficulty. The main feature of this timing system was its infallibly high accuracy.

String breakage in the instrument was rare, owing to the fitting of a safety device that prevented it from being made too taut. As the mass of the string is so very small in relation to the surrounding masses, it is not easily fractured by shock. This could not, however, be said for a fracture in the metallic coating, which did frequently give rise to trouble, since the string, whilst appearing quite in order, became electrically non-conductive and therefore inoperative. This fracture usually occurred at the ends where the string was soldered to its support, or in the centre when it had been made too slack so that it floated to the side of the carrier and rubbed. Such breakdowns were inevitable in instruments used for experimental work, and were a frequent cause of exasperation. Most outfits, however, carried spare string units that could be easily inserted, and in some cases physicians or their technicians were instructed in the art of mounting new strings in the carrier. This, however, was rarely satisfactory as it took considerable training, an exceptionally light touch and much experience.

It may here be opportune to refer to the process of manufacturing quartz strings. As already mentioned, they were first made by the classic method of C. V. Boys, but the selection of the portion of fibre for use was long and arduous. Boys' ingenious method was to shoot, by means of a tightly strung bow, a filament of fused quartz attached to the tail of a light arrow. This fine filament, usually about 20 ft. long, was collected by winding on a sticky wooden frame, and selected portions were used for further processing (9). About 1913 Dr. Keith Lucas, F.R.S., designed a form of tiny electric furnace or heater for drawing the strings, which then began to be made of hard glass. The glass rod was first drawn out by hand in a bunsen flame to about 0.2 mm. diameter, and short lengths were hung vertically in the cylindrical heater. Each length carried at its end a small weight in the form of a glass bead. The heater was switched on, and slowly the glass became plastic, and the weight descended, drawing out the glass fibre. A great deal of skill was required to determine the exact moment for switching off the furnace, otherwise the glass became too plastic, and the weight fell to the ground. If switched off too soon, the weight was arrested early, and the resulting string too thick. Selected strings about 0.003 mm. diameter, which are hardly visible to the naked eye, were then mounted by shellac on a wooden frame, and inserted for a specified period in a chemically silver-plating solution. This was also a tricky operation, as the silver deposit varied greatly without apparent reason; sometimes it was thin or hardly existent, and sometimes thick and spongy. The strings had then to be washed and dried, measured for diameter in a microscope and for electrical resistance. Those of about 0.003 mm. diameter and 3,000 ohms resistance were selected and soldered by a special low-melting point solder into the string carrier, and the tension roughly adjusted by lightly blowing on the string and observing the amount and frequency of the movement. The most delicate operation was then to "burnish" the string by gently stroking it with a thin polished wire, thus to remove any foreign matter, and to render the surface smooth. This satisfactorily accomplished, the carrier was closed and placed in the galvanometer for the final adjustments to be made. These operations called for considerable skill, and were time-absorbing. Nevertheless the resulting string was often of great durability, and letters from users indicate that in some cases a single string has given over twenty years' continuous service. A remarkable record and a very fortunate user.*

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* "Over 22 years ago the Physiology department at the Medical School installed a Cambridge Cardiograph. One fibre has been used consistently; it has recorded thousands of records and thousands of demonstrations have been given. The fibre is still functioning . . ."

(Original letter from New Zealand).

It was probably the frailty of this chemically deposited silver covering that induced Einthoven to experiment as early as 1910 in the cathodic bombardment of quartz fibres with silver ions and he was successful in producing fibres in this way in 1911. A diagram of his system made at that time is reproduced (Fig 5). The information was communicated to the Cambridge Scientific Instrument Co. in secret, and this confidence was respected. Whether Einthoven was disappointed with the process, or whether it was too costly, is not known, but the idea lay fallow until some years afterwards, when Prof. H. B. Williams, in the U.S.A. through the firm of C. Hindle, began making them in this way, and later the Cambridge Company in England began bombarding hard glass with gold ions, and produced the more robust fibres that are in general use today.

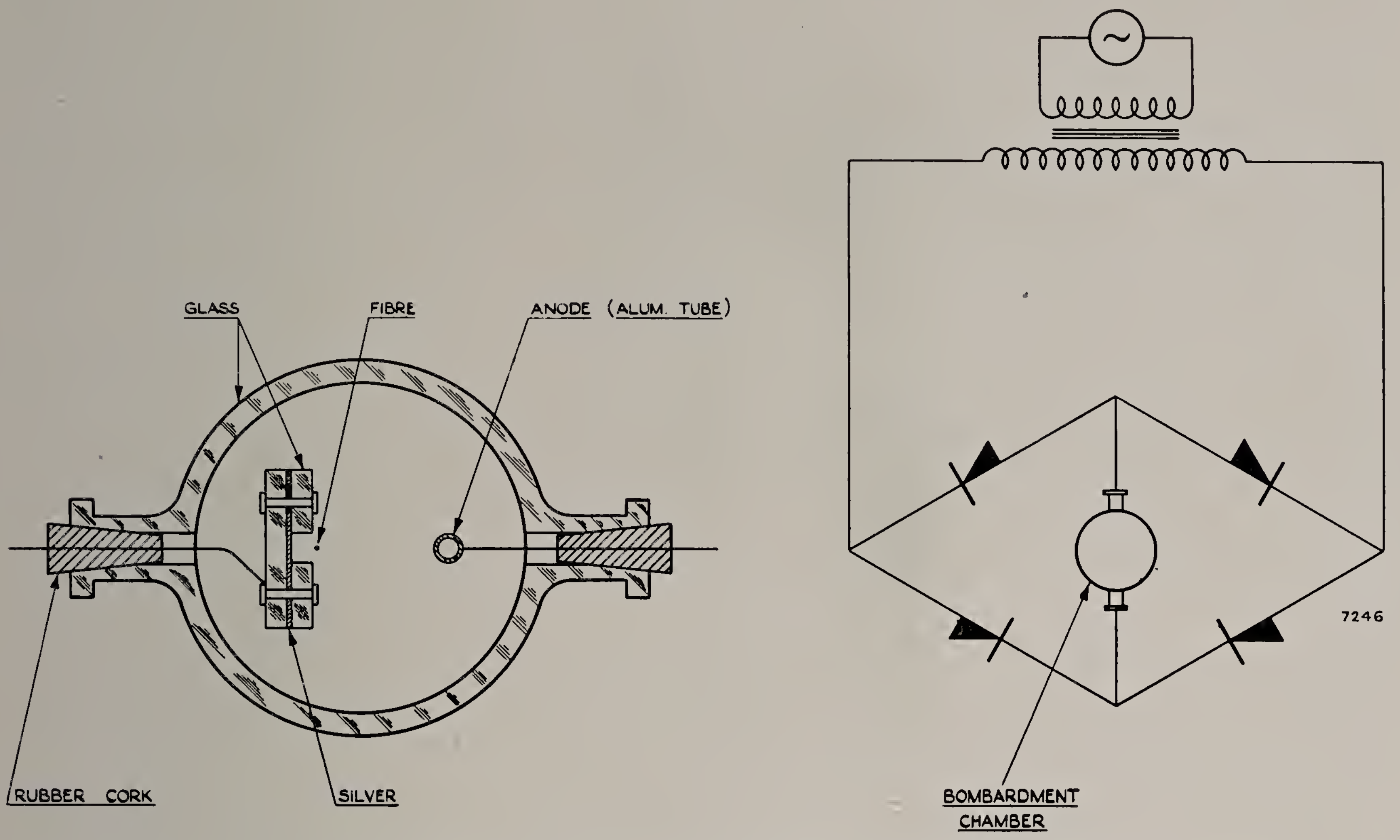

Fig. 5. Diagram of Einthoven's method for bombarding quartz fibres with silver. (1911).

The cumbrous bath electrodes often produced trouble by corrosion of the zinc plates and the fact that zinc oxide crept up and covered the contact terminals. It is a matter of some conjecture as to how much of the frequently mentioned polarization troubles were caused by faulty corroded electrodes, or infrequently changed solutions, thus causing a condition that they were originally intended to prevent.

Notwithstanding these many difficulties, the delicacy of the apparatus and the more difficult technique of operation, these early instruments produced some remarkable results, and reference to the early textbooks will show that the records obtained with them hardly have been bettered.

The permanent nature of the large early installations made it necessary in all cases for the patient to be brought to the electrocardiograph room. This sometimes was inconvenient, and in many of the large hospitals, connecting wires were run from the medical wards to the instrument, making it possible for the patient to be connected in the wards, and the electrocardiograms to be made some distance away. This also involved telephone connections between the operator and the nurse in charge of the patient. Einthoven himself operated his outfit in this way as early as 1905/6 when connection between his laboratory and Leyden Hospital created great excitement. The arrangement was always inconvenient and troublesome, and was finally completely dropped when A.C. power supplies were introduced, with consequent

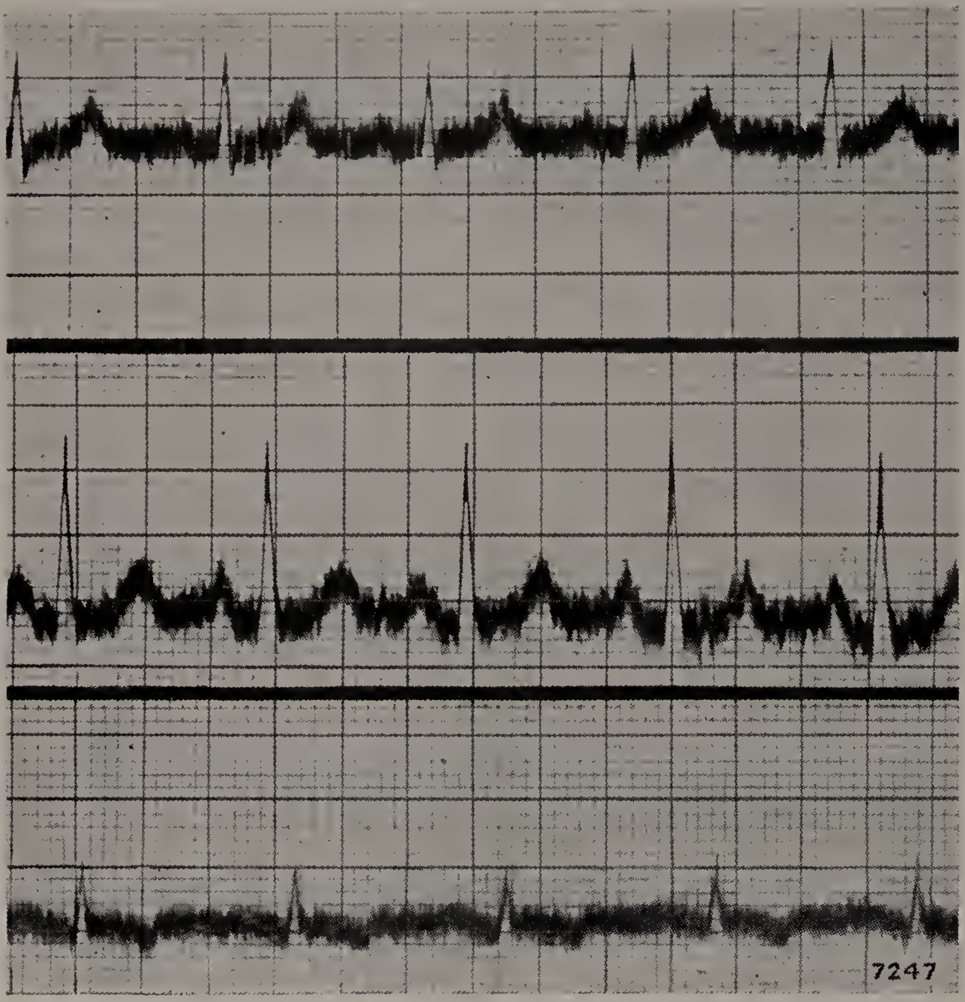

Fig. 6. Electrocardiogram taken over a distance of one mile beween the patient and the instrument. (1916).

increased liability of interference effects on the long connecting cables. Probably one of the most interesting installations of this type was made in 1916, between the University Pathological laboratories at Cambridge and Addenbrookes Hospital, a distance of nearly a mile (Fig. 6). The connecting leads were carried on the Post Office telegraph poles. Satisfactory records were obtained, but with some difficulty, and the installation soon ceased to be operated. Mobile outfits mounted on wheels for transport to the wards were later introduced.

Subsequent to 1920, the growing use of alternating current as a source of power in Great Britain introduced one of the most serious difficulties in the use of electrocardiographs—that of 50 cycle interference on the cardiograph records, although it already had become a source of trouble in the U.S.A. In many hospitals the power was changed from direct current to alternating current and special provision had to be made for energizing the apparatus either from 110-volt storage batteries or rotary converters. This was not found to be very satisfactory, and the apparatus was re-designed to run from a 12-volt storage battery. Even so, alternating current leakage from other parts of the building, and alternating current fields from nearby X-ray or diathermy apparatus often imposed a ripple on the electrocardiogram that made the record unreadable. Many expedients have been adopted to eliminate this trouble, in some cases with complete success, but in other locations it remains a periodic source of difficulty. Unfortunately the 50-cycle wave corresponds very nearly to the somatic waves that are often experienced and are aggravated by imperfectly applied electrodes or discomfort on the part of the patient. If there is only a moderate amount of A.C. interference, and considerable somatic effect, then the effect will be cumulative and render the record unreadable. Physicians have frequently mistaken somatic waves for A.C. interference. Careful insulation and earthing of the apparatus and of the patient will often eradicate the trouble, although in some intractable cases it has been desirable to enclose the patient in a silk covering containing a metallized net fabric that can be connected to "earth". Generally the most efficient method has been to connect to "earth" an unused additional electrode attached to the right leg of the patient.

Later the batteries were dispensed with, and the apparatus energized from the A.C. mains through a rectifier. This was a considerable step forward, especially for portable outfits, subsequently introduced, as it cut out the necessity for charging up and carrying an additional heavy battery. Notwithstanding, some physicians still prefer to use the 12-volt battery in their consulting-rooms, particularly where locations are in old houses with imperfect wiring and increased likelihood of leakage.

It was the pioneer work of Dr. T. Lewis, F.R.S. (afterwards Sir Thomas) in England, Prof. H. B. Williams in the U.S.A. and Professors Wenckebach and Rothberger in Vienna, that greatly progressed the science of Electrocardiography as a clinical and diagnostic tool. Lewis began work in a basement at the University College Hospital Medical School. His research work was somewhat interrupted by the 1914–18 war although his clinical experience was considerably increased during his sojourn in Colchester, where he was appointed Honorary Consulting Physician. It was at this time that he did his notable work on Effort Syndrome. Previously he had published his small book on "Clinical Electrocardiography", (10) which was followed by an immediate demand, by heart consultants in the larger hospitals, for Cardiograph equipment. Many of the larger London and provincial hospitals had by this time been equipped, and papers were issued by many notable clinicians and research workers in ever rising volume. Among these may be noted Drs. John Parkinson (afterwards Sir John), Arnold Stott (afterwards Sir Arnold), Frederick Price, John Hay, MacIlwaine, Strickland Goodall, Thomas Cotton, Philip Hamill, and Cowen, all workers using the early Cambridge instruments.

Lewis was a great experimenter with a most painstaking and deliberate manner. He worked on frogs, small mammals and in the later stages almost exclusively on dogs. He devised excellent experimental electrodes consisting of glass capillary tubes, half filled with kaolin paste and half with copper sulphate solution; the electrode wire was inserted in the solution, and the end of the electrode applied to the exposed tissue. These electrodes were made up in pairs, each limb of which could be separated as desired. With these he plotted the path and speed of the excitation wave induced by artificial shocks from a Du Bois Raymond induction coil. Lewis and his collaborators also employed direct contact electrodes in the form of copper discs attached to the skin with soft kaolin paste . His apparatus was enclosed in a completely blacked inner room entirely lined with galvanized netting as a protection from static charges. He was not a mathematician, had limited electrical knowledge, and required such explanations involving these subjects as were necessary to be given in a simple manner. The writer clearly remembers, about 1919, spending a considerable time explaining Ohms law and the method of calculating resistance from current and voltage, or voltage from current and resistance, etc., by the aid of diagrams drawn on the blackboard fixed behind the door of his instrument-room. It was some time before he was clear, and, at intervals afterwards, he would go to the board and pose himself small calculations of paralleled resistances in order to satisfy himself that he was now competent in that direction. When he had finished, he remarked that many erudite scientists had tried to make him understand these simple laws but they never spoke in terms that he could readily follow. On occasions, later, at meetings such as at the Royal Society Soirées, where research scientists were showing experimental equipment, he would often seek me out to ask me to explain some of the exhibits, always with the remark that he could scarcely ever follow the highly technical descriptions, and that simple, straightforward explanations were rarely proffered. This characteristic is so well exemplified in the great clarity of his published work, his exacting use of simple English, a passion for accuracy, and his dislike of ambiguous technical terms. He was a most kindly and courteous man, although many, at first introduction, were disconcerted by the straight, rather piercing look from his steady eyes, and his slow, deliberate, but very positive manner.

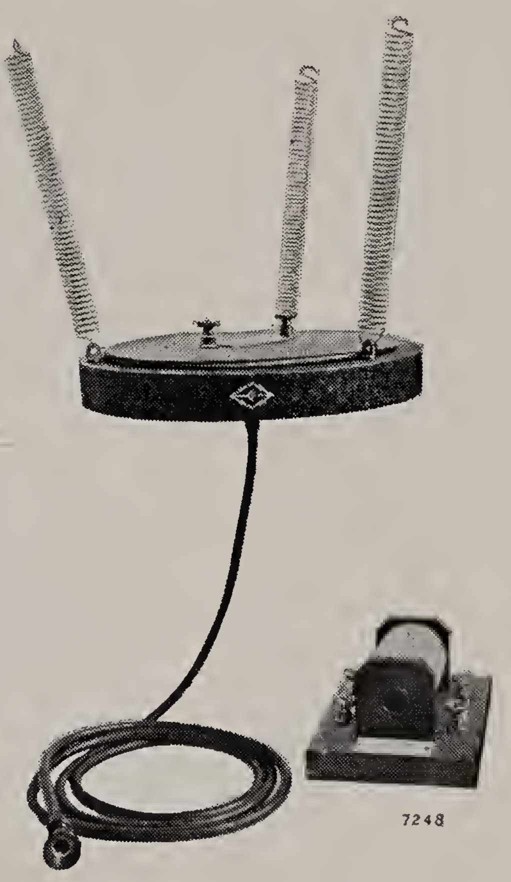

Fig. 7. Heart Sounds apparatus designed for Sir Thomas Lewis, 1913 (Cambridge Scientific Instrument Co. Ltd.).

In 1912 Lewis devoted some attention to recording heart sounds, a subject in which a good deal of work had already been done by Einthoven, Salomonson and others. Indeed, studies of heart sounds had preceded the electrocardiograph by twenty-four years when, in 1879, Stein constructed an "electro-telephonic apparatus for demonstrating the action of the heart and pulse." For Lewis's use the Cambridge Company devised a carbon granule microphone attached to a stethoscope, and connected through a transformer to the galvanometer string on lines suggested by Einthoven (Fig. 7). In order that these sounds could be associated with the electrocardiogram it was necessary to take records simultaneously, and W. H. Duddell

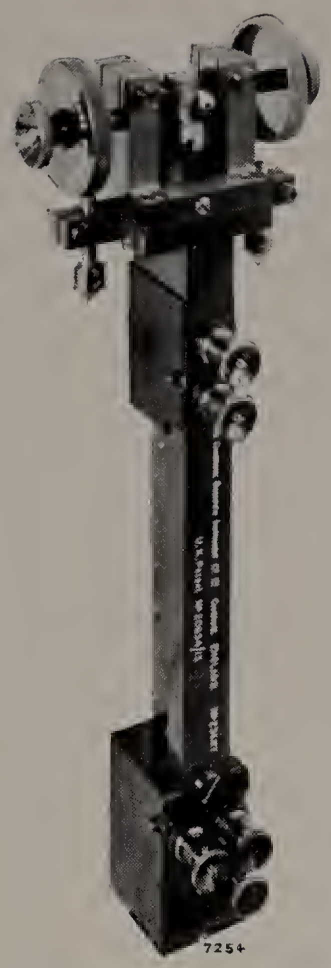

FIG. 8. Double string carrier designed by W.D. Duddell, F.R.S. for Sir T. Lewis 1913 (Cambridge Scientific Instrument Co. Ltd.).

designed, in 1913, a double string carrier for this purpose (Fig 8). The technique of this arrangement was somewhat difficult, but Lewis produced a series of beautiful records, one of the most remarkable of which was a sound record of foetal heart beats with the simultaneous electrocardiogram of the mother (Fig. 9). Later he caused a left-handed galvanometer to be made that could stand side by side with the right-hand model, and was thus able to project the images of four strings and obtain four simultaneous records from different sources, a really difficult technique when one had regard to the considerable associated equipment necessary in experimental work.

For many years the interest in the photographing of heart sounds waned, although in the U.S.A. sets were produced to amplify the sounds, so that they could be heard by a class of students. From 1935 onwards the increased knowledge of valve amplifiers for various purposes, and the design of improved forms of microphones, have stimulated interest, and many manufacturers now fit a heart-sounds attachment, operating a high frequency reflecting mirror galvanometer system, that will record heart sounds simultaneously with the electrocardiogram. There are certain difficulties in recording heart sounds, due particularly to other unwanted sounds, such as respiration noises, adventitious sounds in the bronchii, and surface slip of the microphone attached to the chest wall. Unfortunately these sounds fall in the same wave frequency band as many of the true heart sounds, and tend to obscure some of the low tone murmurs. However, much progress has been made particularly in logarithmic amplification, and those systems made by reputable and experienced manufacturers are sufficiently sensitive and selective to be satisfactory for medical purposes.

From the earliest time it has been possible to record the arterial or venous pulse and respiration movements by means of a Franck capsule or Marey tambour carrying a lightweight lever or arm that is made to move in the light beam, and thus cast a shadow within the illuminated camera aperture. Thus it has been possible to take records simultaneously of pulse wave and heart sounds together with the electrocardiogram. Some work also was done about 1925 in taking several electrocardiograph leads simultaneously from the same subject. This involves the use of two or more control boards, and double string or tandem galvanometers.

The approval of Lewis was sought for any modifications or improvements made in the Cambridge equipment, and he made a thorough and discriminating test on every occasion. Slowly his laboratory acquired a considerable quantity of equipment, and it is interesting to record that in about 1930 it was discovered, by accident, that the rent for his apparatus had never been called for, nor had he ever exercised his right to purchase. At this time he had ceased to be actively interested in electrocardiogaphic studies, and the apparatus had reverted to the hospital, and was under the control of the Medical Research Council. The

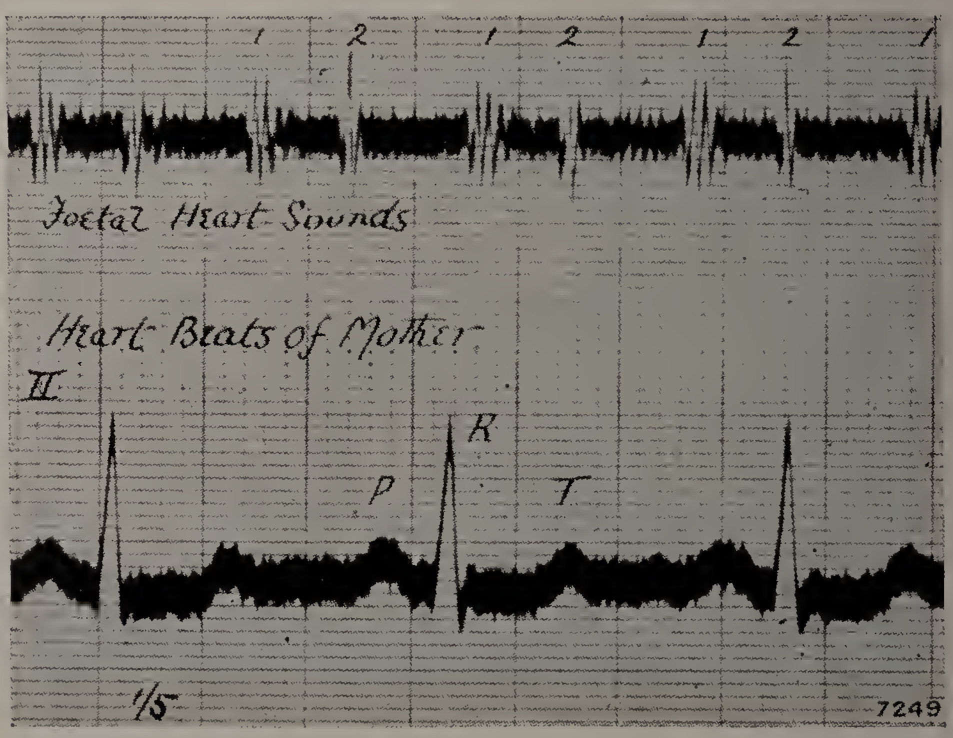

FIG. 9. Foetal heart sounds simultaneously recorded with electrocardiogram of mother, by Sir T. Lewis (1913).

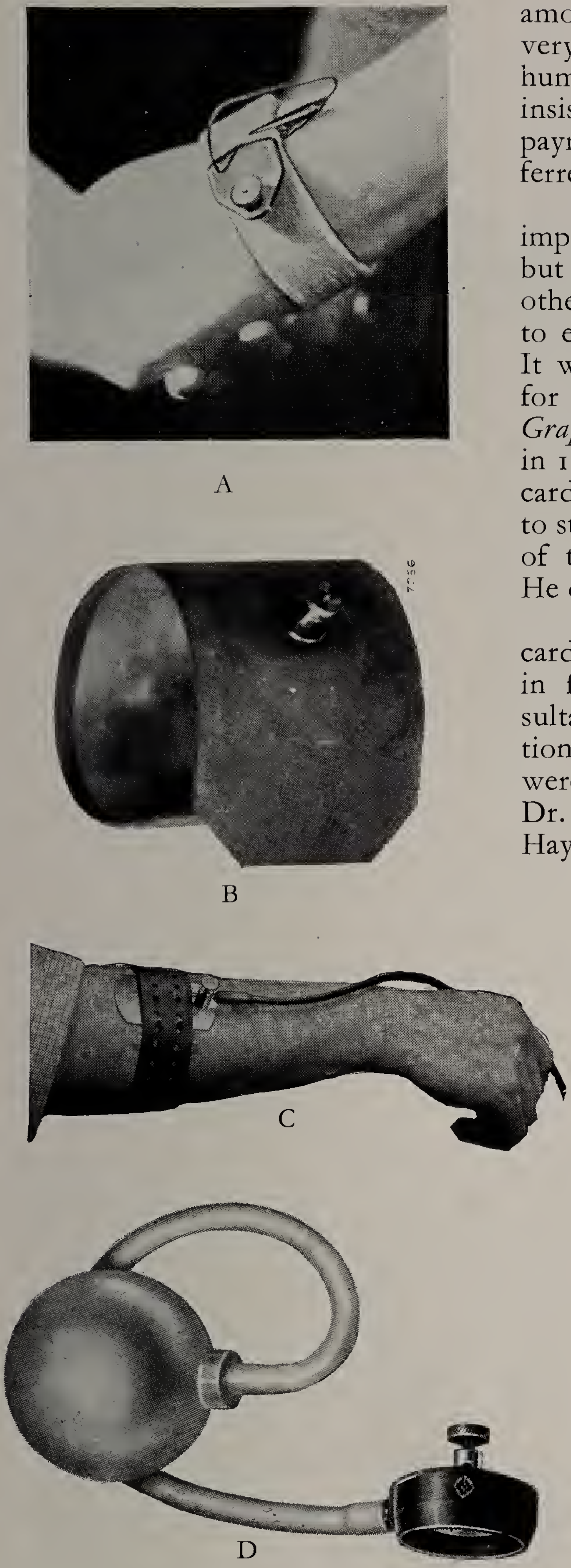

Fig. 10.
A. Strap electrode by Barron (1920).
B. Strap electrode by Cohn (1920).
C. Direct contact plate electrode.
(Cambridge Instrument Co., Ltd., 1930).
D. Suction electrode by Burger (1932).

amount of indebtedness over the years had reached a very high figure, and upon the matter being rather humorously mentioned "*én passant*" to Lewis, he insisted that the Council should make a nominal payment, and the Cambridge Company then transferred all the apparatus to the Medical School.

Lewis was responsible only for suggestions of improvements : he knew precisely what he wanted, but had no part in design. It was the function of others to produce, how they would, the apparatus to enable him to obtain the information he sought. It was a great privilege to have known and worked for him. His best known work, "*The Mechanism and Graphic Registration of the Heart Beat*" was published in 1921 (11). In his later years he abandoned electrocardiograph researches, and devoted his great ability to studies of the circulation. He was elected a Fellow of the Royal Society in 1918 and knighted in 1921. He died in 1945.

Towards the close of the 1918 War, the electrocardiograph was fully established, and orders flowed in from hospitals all over the world. Cardiac consultants also began to use the instrument for consultation purposes, and among the first in this country were Sir John Parkinson, Dr. Strickland Goodall, Dr. Frederick Price, Dr. Wardrop Griffiths, Dr. John Hay and Sir Arnold Stott. In addition to the modifications already mentioned the apparatus was changed in few respects, the arc lamp was replaced by a Point-o-lite lamp thus dispensing with the water bath, and the vibrating time marker by the Rayleigh synchronous motor. The galvanometer was made less bulky, and the length of the "string" shortened, but the essential sensitivity and technique remained unchanged. The annoying electrode baths, although reduced in size, remained standard practice in Great Britain until about 1920 when the writer introduced a flexible copper mesh strap electrode enclosed in a saturated flannel jacket. Simultaneously Cohn in America produced a metal foil electrode attached to rubber straps (12). Cohn's electrodes were convenient to use, and were generally adopted for consulting work, although many hospitals continued to use the baths. It is an interesting fact that this, a most simple type of electrode, should be generally adopted at so late a date, after the many years of difficulty and investigation undertaken by Einthoven and others (Fig. 10). Was the much-talked-of electrode polarization a bogey?, and were some polarization effects inherent in the elaborate electrode systems produced earlier? The fact is that the metal contact electrode of

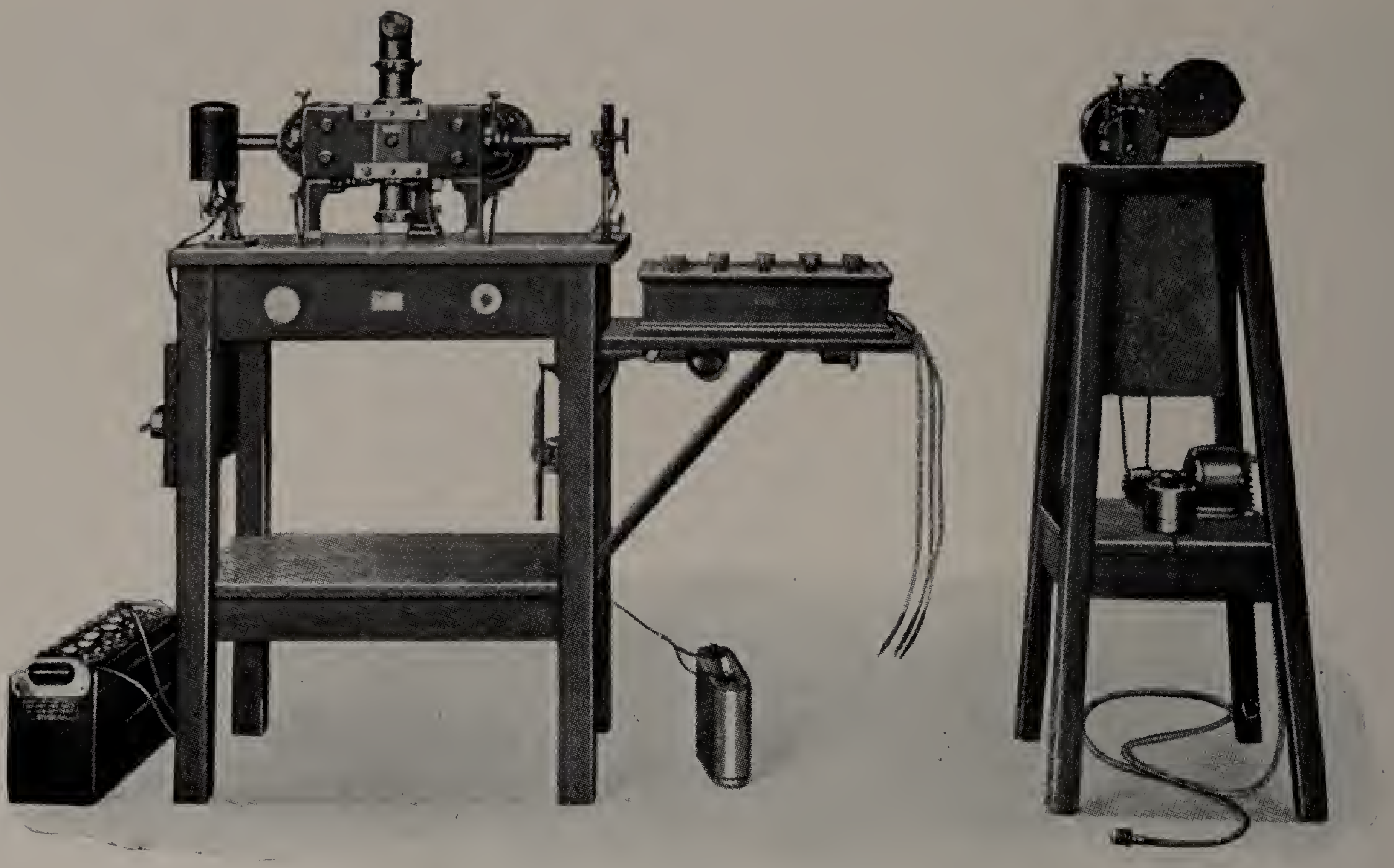

FIG. 11. Hindle Electrocardiograph outfit (U.S.A.) c. 1918.

Cohn and the subsequent direct contact electrodes produce no such difficulties, and polarization is now rarely encountered. This anomaly has its counterpart in the early straining for solid foundations. It was commonly believed that this delicate instrument must be abnormally sensitive to vibration, and in some cases the instruments were installed in basements where specially reinforced concrete floors had, quite unnecessarily, been constructed. It is for this reason that almost all the early cardiographs were installed in basements, although later almost identical outfits were satisfactorily installed in rather rickety conditions in the upper rooms of older houses frequented by consultants. The writer remembers that Dr. Strickland Goodall specially selected his inconvenient basement consulting-rooms in Harley Street with this point in mind.

Meantime in the U.S.A. Professor H. B. Williams, following a visit to Einthoven, caused a complete equipment to be constructed in his laboratory. His mechanic was Mr. Charles Hindle, who completed the instrument about 1910. A considerable demand grew for similar instruments, and Mr. Hindle formed a private company, commenced manufacture, and produced an instrument which was marketed in the United States of America (Fig 11). Prof. Williams retained an interest in the Hindle company, and acted as adviser and consultant, in many respects as had Dr. Lewis in England. The Hindle concern was restricted entirely to the manufacture of electrocardiographs, and a complete instrument similar in many respects to the British instrument was independently developed. Later there were other makers in the U.S.A. but for many years the Hindle instrument remained the only type available on the American continent. Most of the extensive early work of American physiologists and physicians was carried out on Hindle instruments. As in England, successive improvements were effected, but no really great changes took place until about 1920, when the need for an instrument that could be taken into hospital wards was urgently felt as, up to then, it had usually been necessary to move the patient to the instrument. This need was quickly met by mounting the outfit on a wheeled trolley; it was, however, a cumbrous thing to move about. It will be observed that by this time the bogey of fragility and solid foundations had been materially eliminated (Figs. 12 and 13).

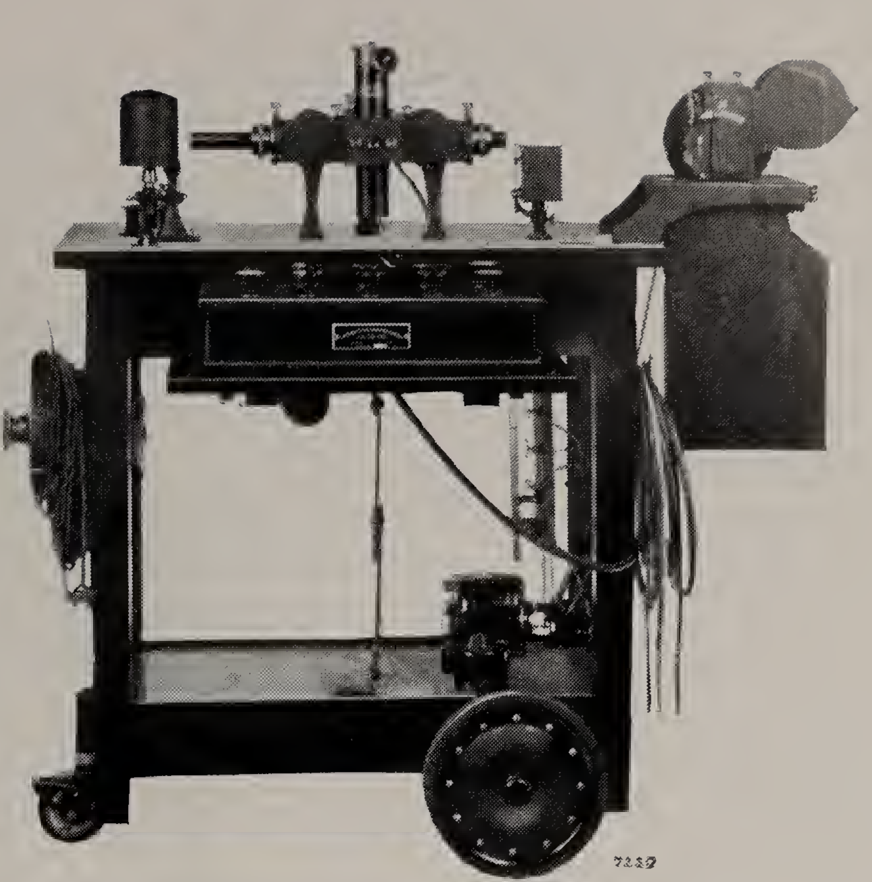

Fig. 12. Hindle-Cambridge mobile electrocardiograph 1920 (U.S.A.).

In 1922 an amalgamation between the Cambridge Instrument Company and the Hindle Company was effected, and the latter changed its name to the Cambridge Instrument Company of America. Mr. Hindle retired from the organization, but Prof. Williams continues to take a lively interest. This association brought about close co-operation and exchange of ideas, and although American practice, originated by Williams and Hindle, differs somewhat from British practice, much of value has been incorporated into the British instrument from its American counterpart. There is little doubt that the American Company were, in some respects, more progressive than the British Company in this field. This arose out of an earlier and more persistent demand on the part of the more instrument-minded American medical practitioners. Changes were, however, closely related although they usually came into production earlier on the American continent.

The demand for a transportable instrument for consulting work became insistent at about 1928, and in this country, largely on the insistence of the late Sir Maurice Cassidy and Dr. Donald Hall, a suitable apparatus was made which came into full production in 1930 (Fig. 14). The American counterpart had been made rather earlier. This had become possible owing to the introduction of new magnet steels of high magnetic quality and permanency, which made it possible to manufacture a permanent magnet galvanometer having only a fraction of the size and weight of the electro-magnet model, but with similar characteristics. The fibre was shortened from 10 cms. to 4 cms. and the Point-o-lite lamp replaced by a high intensity filament bulb. The time marker was clock-driven, with an automatic winder. The camera underwent radical redesign, and was adapted for the use of films wrapped around a drum which could be exposed in three sections. A special magnetic damping device caused the speed of rotation to be absolutely constant over the whole length of the film. A portable developing tank was designed that could be operated in daylight, thus enabling films to be processed at a patient's house.

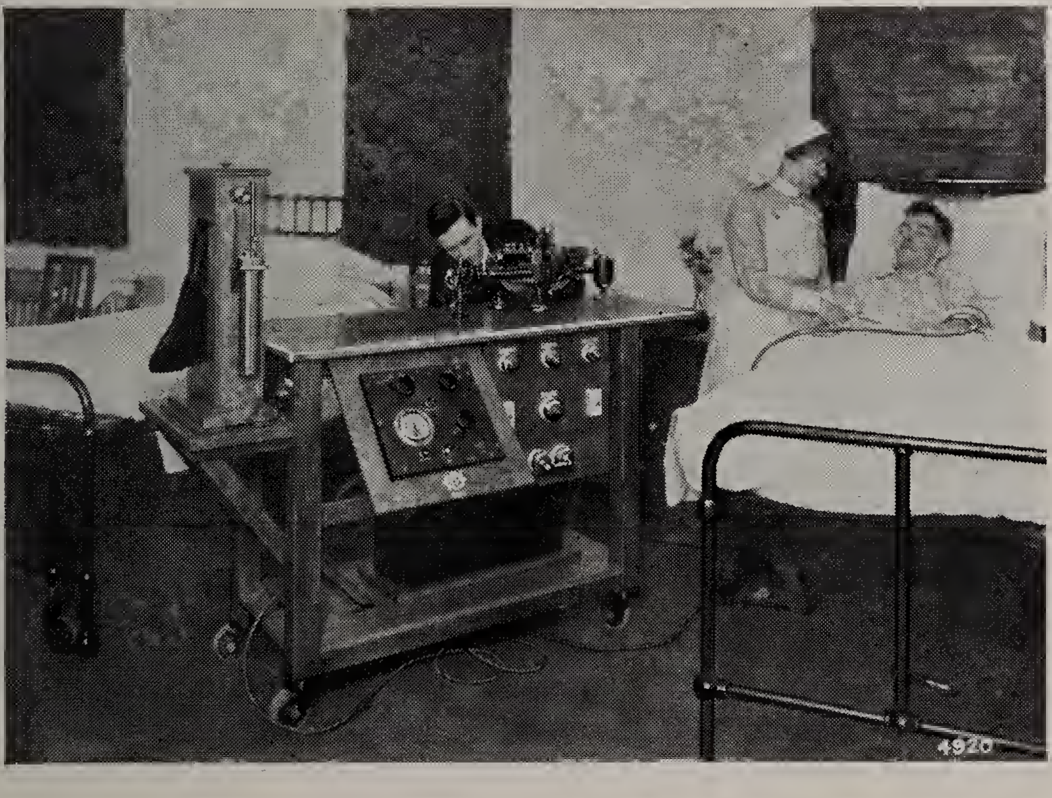

Fig. 13. Cambridge (England) mobile electrocardiograph (1920).

At first Lewis had no great leaning towards the

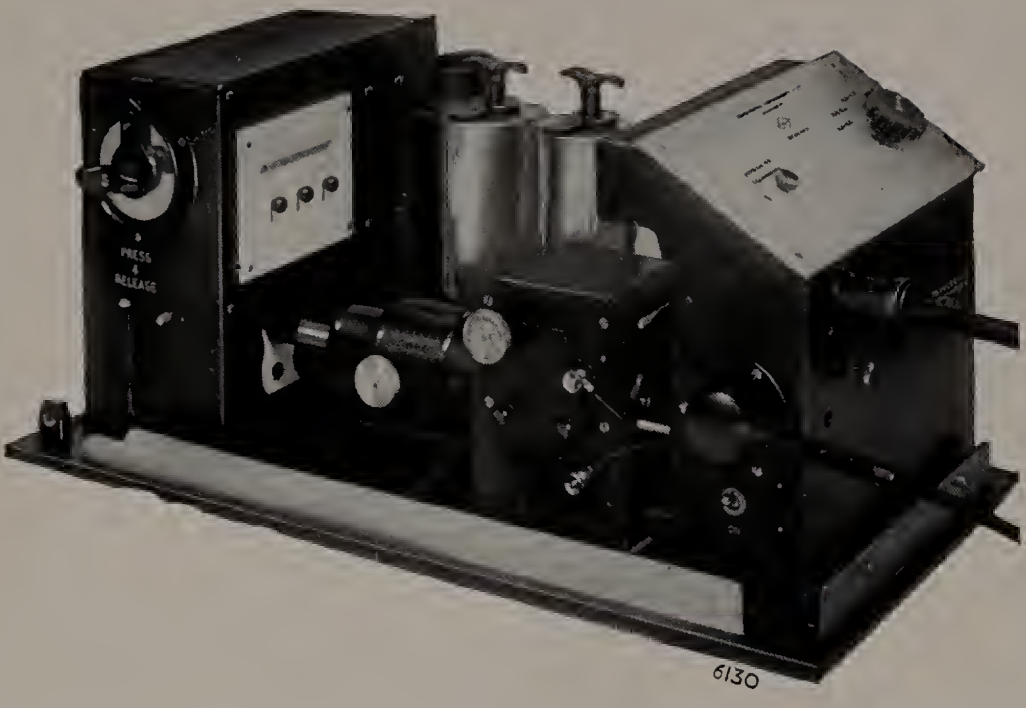

Fig. 14. Cambridge (England) transportable electrocardiograph for consulting work. 1929. (This model, fitted on a trolley, later became the Cambridge standard outfit).

necessity for a portable equipment, largely because he had doubts as to the practicability of retaining the necessary characteristics in a much smaller instrument. He feared that the designers whilst straining for lightness and compactness would, in some degree, forego accuracy, and he would not allow himself to be associated with anything that would be regressive in this sense. It was, in some measure, because of this lack of enthusiasm that the British Cambridge Company delayed production until extended tests of a prototype had proved to Lewis's satisfaction that a suitable instrument could be marketed.

Radical change was later made in the form of skin compensation. Instead of using a potential slide wire, the skin current was blocked by a high capacity condenser. This greatly simplified the operating technique and eliminated fibre wander due to respiration or changing skin current conditions. Theoretically, it was not perfect, but was proved not to produce any material distortion of the electrocardiogram. The weight of the complete apparatus was at this time reduced from over 3 cwts. to 63 lbs., and the size from overall 5 ft. × 2 ft. to 2 ft. × 1 ft. The outfit was driven from a 12-volt battery, which also had to be carried. A large number of these early transportable outfits were made, and when fitted to a trolley formed a convenient mobile outfit. Thus the large table outfits became obsolete, and no more were made. Despite this great change in form, it was still considered too bulky as a truly portable outfit, and further pressure led to still further radical modifications.

In the meantime, the most sweeping changes had taken place by the introduction of cardiographs that dispensed with the string galvanometer, and employed a system of valve amplification operating an oscillograph system, or used in conjunction with a cathode ray screen. Messrs. Siemens & Halske in Germany were the first to produce, in 1921, a portable Cardiograph working on a valve amplified oscillograph system. The original design has undergone many modifications, and is now much improved. This type of instrument is now widely employed on the Continent of Europe. In the U.S.A. a large number of firms not previously interested in cardiographs entered the market, and the Cambridge organization had to decide whether to adopt the new methods, which had inherent advantages, or to concentrate on remodelling the Einthoven instrument. Shortly afterwards the same problem arose in Gt. Britain, and after a full and lengthy investigation of the many pros and cons it was decided for the time being to continue with the established Einthoven instrument, which was still accepted as the standard for comparison.

A few remarks on some of the factors that at this time influenced this decision may not be out of place.

One advantage claimed for the valve operated instrument was that it was not affected by high electrode contact resistance. This was countered by an investigation which showed that the normal contact resistance of about $2{,}000^{\omega}$ could be increased by × 5 without any material change in the electrocardiogram taken with the Einthoven instrument. The valve instrument appeared, on test, to be more prone to alternating current interference than the Einthoven while variation in valve characteristics and deterioration in use altered the carefully calculated amplification characteristics over the wave band employed in cardiography. This required that replacement valves be carefully selected and matched and careful attention be paid to battery voltages. Examination of some early electrocardiograms taken on valve operated instruments showed marked differences from those obtained with the Einthoven instrument.

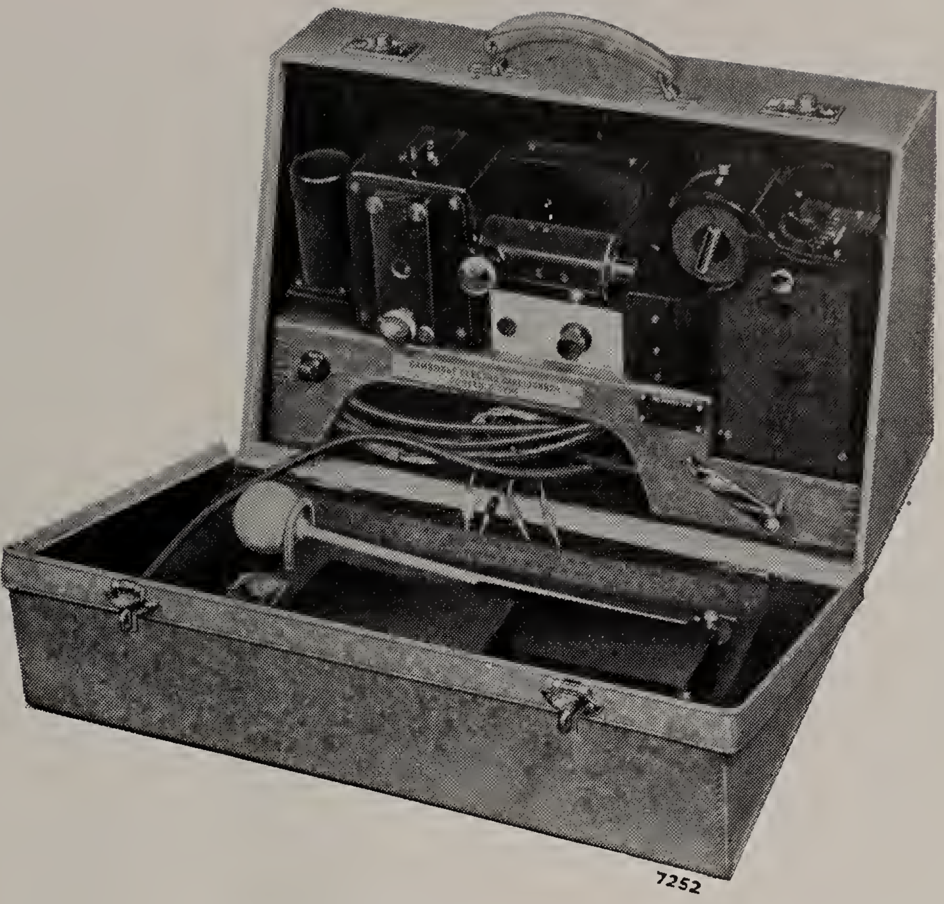

Fig. 15. Cambridge (England) suitcase portable electrocardiograph (1938).

Another advantage claimed for the valve system lay in the fact that it was possible to construct the instrument so that the record appeared on a cathode ray screen before and during exposure, thus making possible a preliminary examination prior to photographic development. Upon medical advice this was thought to be more apparent than real. A proper cardiographic analysis could only be made by careful measurement of the characteristics of the finished record. Reliance on visual indications of a fleeting image might, in fact, prove a snare, and give rise to faulty snap diagnosis. It is true that the more common abnormalities would be easily recognized, but such could also be determined by ordinary clinical means. Examination showed that the Einthoven instrument was fully capable of accurately responding to the whole range of frequencies met with in the clinical electrocardiogram, and unless future work suggested that higher frequencies occurred than had been recorded to date, the instrument was fully adequate for its purpose. Cardiograms from the Einthoven string instrument remain the standard of reference.

In these circumstances it was considered that the introduction of the complication of an amplifier system was unnecessary, and since the "bogey" of great fragility had also now been exploded, no advantage could be obtained from the scientific angle. There remained the questions of size, weight, and production cost. These were carefully investigated, and a conclusion reached at that time that radical redesign could satisfactorily solve each of these problems.

The answer to the early valve instruments was presented in the U.S.A. in 1936 by the Cambridge Company's Simpli-trol model, weighing 30 lbs., and in England by the Cambridge suitcase Portable, complete with electrodes and all accessories, also weighing 30 lbs. (Fig 15). These instruments maintain the characteristics of the original Einthoven instruments, but are much easier to operate, and have devices that have eliminated almost all of the troublesome factors that have been earlier referred to. From an original equipment occupying a whole room, and a combined weight of not less than 6 cwts., to an instrument in a suitcase weighing 30 lbs., is a fair accomplishment, albeit that it had taken nearly forty years to accomplish ; especially when the ten war years are taken into account, during which any marked development was stagnant. Later continued pressure and improvements in design caused the Cambridge companies to modify their view and to produce a valve operated instrument.

Little has been written in this Monograph of the recording of heart sounds as this subject, whilst closely associated with Electro-cardiography, is considered out of the scope of this publication. Suffice to say that the introduction of valve amplifiers and new forms of piezo electric microphones have greatly extended the possibilities of valuable work and much is now proceeding. This revival of interest has been greatly stimulated by the work of Wells, Rappaport and Sprague (15) in the United States of America, and by Dr. W. Evans in Gt. Britain. Many cardiographs now are made capable of taking simultaneous electrocardiograms and heart sounds records.

It would not be appropriate to conclude this review without noting some of the developments on the medical side that have caused changes in technique and design on the part of instrument makers. As already indicated, little fundamental change had taken place in the apparatus or technique until 1934, when the Cambridge organization advanced the direct contact plate electrode. This had results out of proportion to the convenience that it conferred on the user. Prior to this, the electrodes generally used were the baths already described, or imperfect strap-on electrodes of metal foil and saturated flannel. The bath electrodes were quite inconvenient for bedside use with the patient prone, and could not conveniently be used with a transportable instrument. The establishment of direct contact electrodes opened the way to the use of chest electrodes as well as greatly advancing the possibility of portable and bedside outfits. Much of the credit for the satisfactory behaviour of the direct contact electrode is due to the use of the special electrode jelly, with which the skin is massaged prior to the application of the electrode. This jelly is a sterile electrically conductive lubricant with a very slightly abrasive action, and when properly applied reduces the skin resistance to a low value. This jelly was first commercially introduced by the Cambridge Instrument Company of America, and is now universally used. Of other types of electrodes produced may be mentioned the self-retaining suction type, due to the late Dr. Burger of Switzerland, and especially suitable for chest connection. A small, specially constructed pattern has also been developed as an oesophageal electrode.

The possibility of taking electrode connections from the chest wall had been recognised from the earliest times; indeed Waller in 1887, Bayliss and Starling in 1892, and Einthoven in 1895, had published results obtained by using the capillary electrometer. Later, many workers experimented with disc electrodes placed at varying positions on the chest wall, used in conjunction with one of the limb electrodes or with an electrode placed on the back. Among these may be mentioned Lewis and Drury. It was not until about 1930 that the chest connection became seriously established as a routine lead connection in certain types of abnormalities. The introduction of chest electrodes brought about a new series of electrocardiograms, and a large number of research publications followed. (13)

The standardization and nomenclature of these various lead connections was considered by the appropriate medical bodies concerned with cardiology in the U.S.A. and Gt. Britain, and the newly established chest connections then denominated Lead 4 came into general use. This necessitated alteration of the selector switches on most cardiographs, and the addition of extra connecting leads and electrodes, thus constituting the first real addition to the established Einthoven convention.

Later Dr. F. N. Wilson introduced a new method of connection involving the addition of series resistances of $5{,}000^{\omega}$ in each lead, and connecting three of the limb leads together as a fixed electrode and a fourth exploratory electrode was attached to selected points on the chest wall. These he named the Wilson Unipolar leads, (7) and they were denominated V_1, V_2, V_3. Later, E. Goldberger made further alterations to the connections which discontinued the use of the $5{,}000^{\omega}$ resistances and connected together two limb electrodes in sequence; these were called the Augmented Unipolar Limb leads, (8) and named aVr, aVl, and aVf. Both the Wilson and Goldberger connections have now found widespread use, and have greatly increased the usefulness of the electrocardiograph as a diagnostic tool, *e.g.* especially in cases of infarction regarding the influence of the position of the heart, etc. They have largely displaced the earlier Lead 4. These new connections created even greater departures from the Einthoven conventional use of the plain triangle of connections, and although the whole series of electrocardiograms may not be necessary in all cardiac examinations, no fewer than twelve lead connections are now established, and many others used for special investigation.

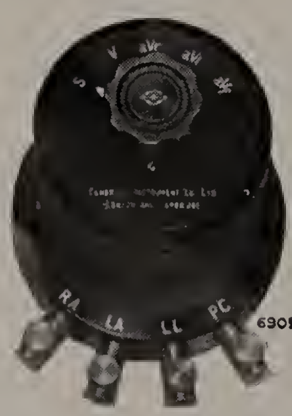

Fig. 16. Cambridge Unipolar Lead Switch Assembly.

To enable these to be conveniently photographed, a special switch, produced by the Cambridge organization, was introduced. This is called the Unipolar Lead Assembly, (Fig. 16) and enables both Wilson and Goldberger connections conveniently to be

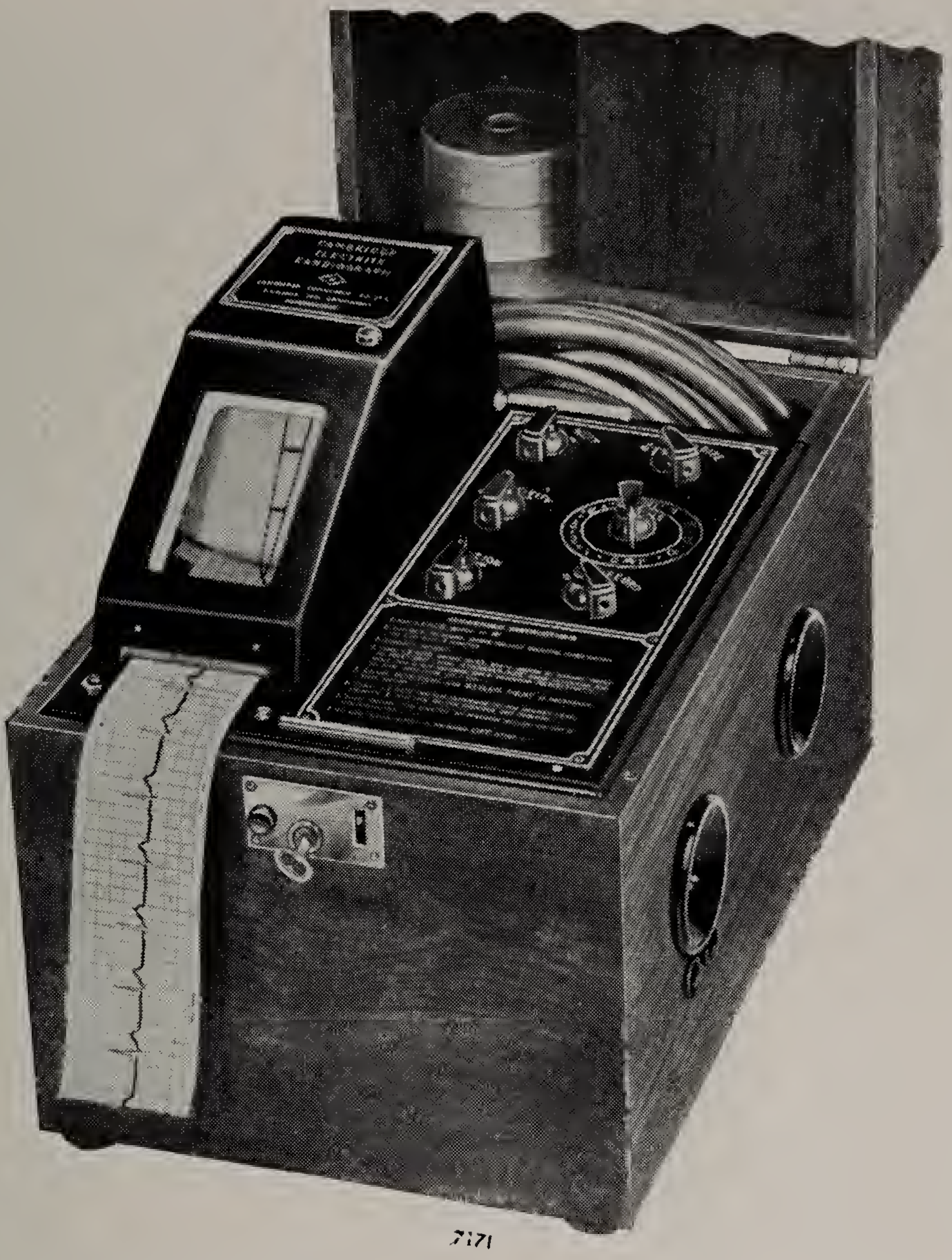

Fig. 17. Cambridge (U.S.A.) "Simpli-scribe", and (England) "Electrite" direct writing portable electrocardiograph. (1948).

made on a conventional four lead cardiograph without disturbing the patient. Modern cardiographs embody a selector switch for taking the full range of leads.

There has also been considerable work done in relation to records taken after graded exercise, and much interesting and valuable information has been elicited. This has necessitated the use of strip records of considerable length. In America the continuous film or photographic paper camera had always been standard, and thus the existing camera was already suitable. In Great Britain the short film with records side by side had been standard for many years. These developments indicated the need for a change in policy, and the latest British instruments now also use, or may be adapted to use, the continous strip camera.

When Lewis ceased his cardiographic researches in about 1930 he left the subject largely as Einthoven had conceived it, and the equipment, though much improved, was fundamentally as Einthoven had designed it. Along with many others, all over the world, Lewis had contributed an enormous amount to the understanding of the different types of records obtained in most cardiac abnormalities. Many felt that there was little more to be accomplished except in the application of these researches, but there were still many fields to explore, many abnormalities to be explained, and cardiographic changes to be recorded. Chest leads, unipolar and augmented unipolar leads opened new doors which are now in the high tide of investigation.

The development of valve amplifiers has introduced an important and fundamental weapon in the armoury of the Scientist who is investigating problems where only small

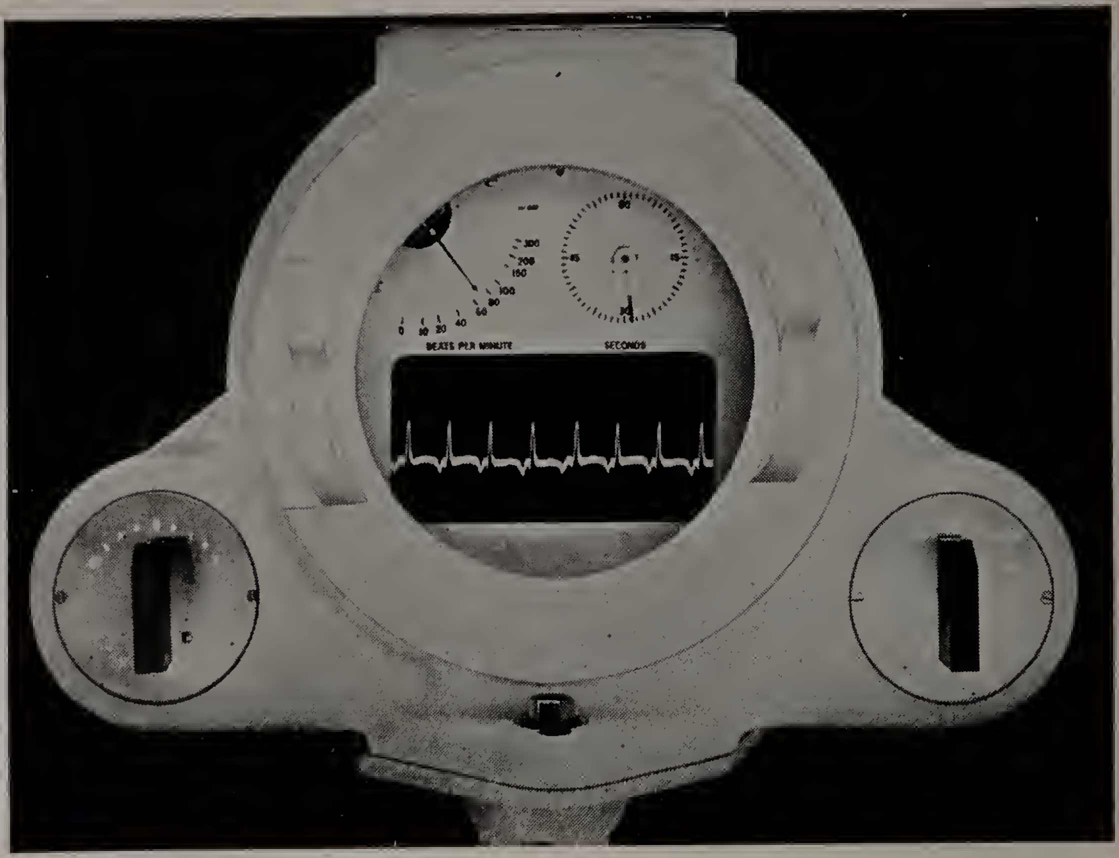

Fig. 18. Cambridge (U.S.A.) Cardioscope designed for use in operating theatres (1950).

electrical power is available. Heretofore only the most sensitive instruments could be used; now, with power amplified as much as is desired by valve circuits, less sensitive and more robust instruments could well be employed.

One drawback of all cardiographs, up to this time, was the need for processing the resulting photographic records before an analysis could be made. This was particularly irksome in consulting work, that may often be done away from the consulting room. It was clearly recognised that a direct writing cardiograph, of proven accuracy, would be a great step forward to meet such requirements and many manufacturers became interested in such developments. Such direct writing instruments dispensed with the Einthoven string galvanometer and replaced it by a robust d'Arsonval galvanometer carrying a writing point in the place of the conventional pointer.

Probably the first pen recording valve amplified galvanometer capable of this work was produced in 1929 by Dr. Bryan Matthews (now Sir Bryan Matthews) working in the Physiological Laboratory in Cambridge. (14) The instrument was designed for recording nerve impulses but it was realised by the inventor that it could be applied to cardiography, and an instrument was made and tested by Sir John Parkinson. This model was taken up by a commercial firm (The Clifton Instrument Co. Ltd.) and a few instruments were made but it did not have much success. Since then many other manufacturers have introduced designs and some of these are now being marketed. Among the best known are the Cambridge Company's Simpli-scribe (in the U.S.A.), Electrite (in Gt. Britain) (Fig. 17) and the Elmquist Models. The latter may be multi-channel instruments for recording several simultaneous phenomena.

The advantages of such clinical instruments are indisputable and it is a fair conjecture that the tendency will be increasingly in this direction, but the performance will require to be proved and checked against the established standards which for the present remain the String Galvanometer Assembly.

Valve Amplification and cathode ray tubes have also made it possible to construct an instrument for use as a monitor in the operating theatre for use during cardiac operations or whenever the anaesthetist and surgeon desire to observe the patient's electrocardiograms throughout an operation. Such instruments are considered by many to be essential equipment. Some models are complete in themselves while others are supplied as ancillary equipment to

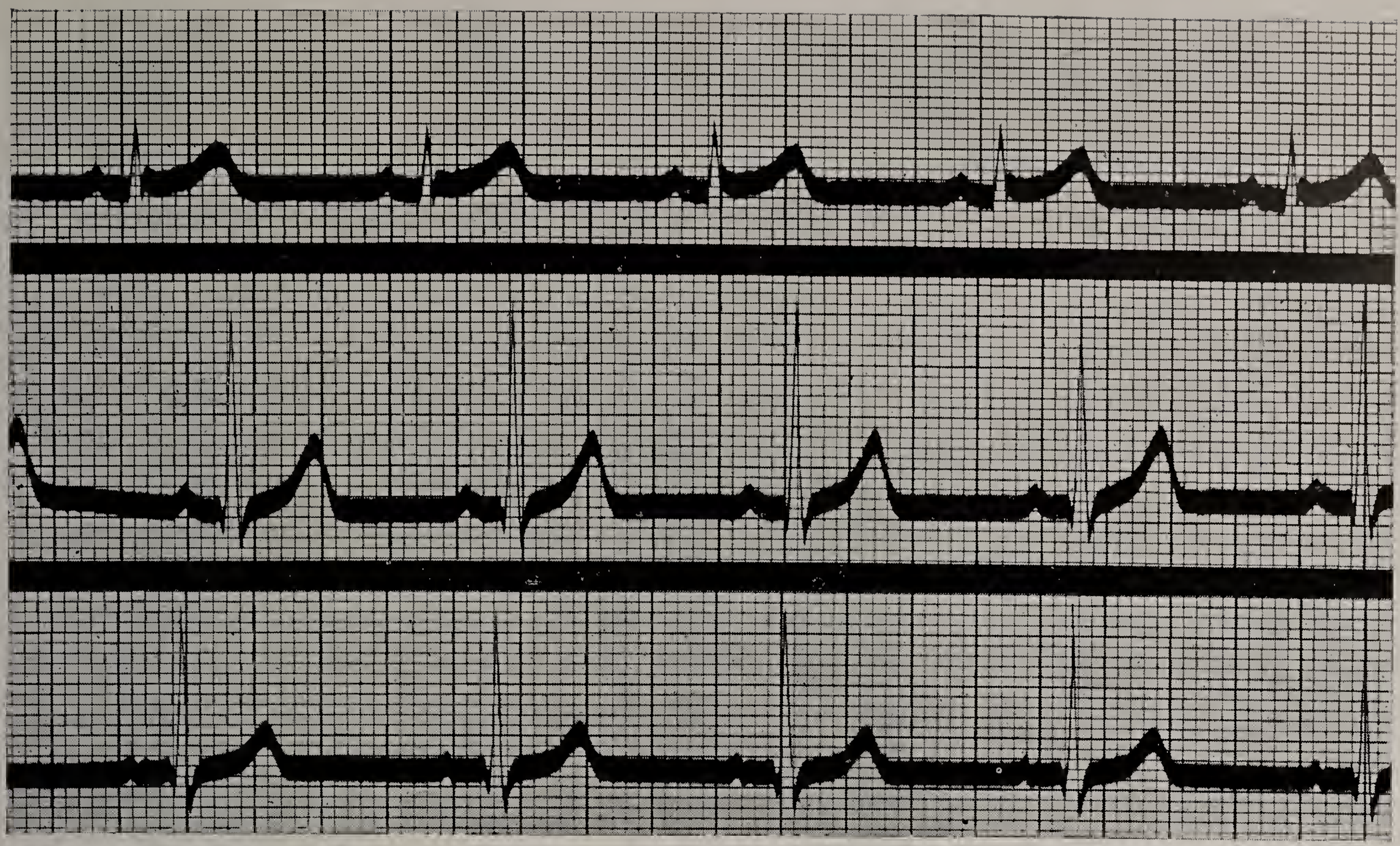

Fig. 19. Modern three lead electrocardiogram taken on instrument illustrated in Fig. 14.

the valve operated cardiograph and are energised directly from it. Thus the anaesthetist can directly observe any changes that take place in the wave shape and may cause specimen records to be made at any point that he deems of importance (Fig. 18).

Possibly no other twentieth-century medico-scientific invention has had more far-reaching results than the electrocardiograph, or has become so universally used in every hospital and by all practising cardiologists throughout the world. It has been the product of close co-operation between the medical scientists and the manufacturers; hardly has a need been expressed than it has found its response in a piece of practical equipment. Laboratory extemporization has been examined by the manufacturers, and put into practical and marketable form. In all the years it has been the happiest and most productive of associations; long may it continue.

We began with Willem Einthoven, and it would be a fitting tribute to his genius to compare a record taken on his original equipment in 1903, (Fig. 1) and a similar record of today, after nearly fifty years' continuous world-wide development (Fig. 19). Technically they are indistinguishable, and many physicians today would be happy to make, consistently, such excellent electro-cardiograms as were produced on the mammoth instrument made by this great experimenter.

Of the great pioneer triumvirate, Einthoven, Williams and Lewis, only Professor Williams remains and it is to him that this monograph is respectfully dedicated.

Some biographical notes on Professor W. Einthoven appear overleaf.

WILLEM EINTHOVEN

Biographical Notes

It may be of interest to conclude with a few remarks of a biographical nature on Willem Einthoven. He was born in 1860 and studied at Utrecht University under Donders and Snellen and was therefore at first mainly interested in Optics on which subject he published some early papers. That he showed extraordinary brilliance is indicated by the fact that he was made a Professor in Leyden when he was about 24 years of age and before he had fully completed his qualification. It was a special appointment termed "an appointment on credit" that is, he was given credit for what he was expected to do rather than for what he had done. That this appointment was amply justified, history records.

By this time Einthoven's main interest lay in electrical developments in relation to physiology and his laboratory was wired throughout to a generator installed in the basement. It has been said that Einthoven was too poor to pay for his own medical studies and that he signed on for military service in which case the authorities paid for the studies on the understanding that when qualified he should take up full time military service. When he was so unexpectedly appointed a professor these official loans had to be repaid.

Einthoven was in the habit of arriving at his laboratory in the morning (usually at about 11 o'clock) on his bicycle clad in a quite original style of combined coat and cape that he continued to wear during his life. His bicycle remained his constant form of transport during most of his working life and he could be seen at anytime night or day in all weathers pedalling to and from his laboratory and in the early years even taking journeys to Amsterdam and back (60 miles in all) to attend the monthly meetings of the Royal Academy of Science. Once in his laboratory he took off his shoes and put on slippers and then removed his collar and tie and settled to uninterrupted work until the laboratory porter (on instructions from Mrs. Einthoven) interrupted him at 5 o'clock to say "Professor, it is 5 o'clock." This message was repeated at half hourly intervals, usually acknowledged by a nod and no cessation of work, until at a convenient time, often as late as 8 o'clock, Einthoven rose, reclothed, and cycled back home.

Beyond his work and his family, Einthoven had few interests. In those days in Holland there was a famous dramatist, Hieremanns, whose name was a household word rather as Bernard Shaw's is in this country. It is recorded that on one occasion two assistants were discussing Hieremanns' name and work in Einthoven's hearing when he turned and said "Hieremanns? who is Hieremanns?" He was, however, interested in music and at one time played the violin. Of holidays nothing is known and those with personal knowledge of his family life doubt if he ever took one. He was a great walker as well as cyclist and these were his only forms of recreation.

He was a very friendly man and took great interest in those who worked with him, but was also curiously modest. At first his experiments did not greatly impress his contemporaries in Leyden, indeed by the Medical faculty he was considered rather odd and the first marked recognition came from physiologists from overseas. He was however never discouraged and his dogged patience and perseverance was an inspiration to all who worked with him. It was a disappointment when many of his most promising students and assistants gave up experimental physiology and went into medical practice but he fully realised that, at that time, there were few financial inducements for the pure research worker, and he never held his disappointment against them, since he remained in close correspondence with many of them throughout his active life.

Einthoven lectured to students on physiology, the normal course taking two years, but an extended course could occupy five years. His great interest lay in electro-physiology and in this he was an absolute master. Among his students at the relevant period was Jolly who afterwards became Professor of Physiology in Cape Town, Bataerd, later Professor of Physiology in Stellenbosch and A. Pipjer, later Professor of Pathology in Pretoria, all in South Africa.

It may be of interest that the Laboratories next to that of Einthoven in Leyden housed both Lorentz the theoretical physicist, and Kammerling Onnes who at that time was working on the liquification of Helium. What scientific history was being born, during that period, in the little square in a small University town! There was sometimes a little trouble between these most eminent workers. Einthoven complained that the strong electric currents used by Kammerling Onnes upset his electrocardiograph and they complained that his dogs made too much noise. Einthoven who was not strong in mathematics was in the habit of taking his mathematical problems to Professor Kluyver, the Professor of Mathematics in Leyden, and a great admirer of both the man and his work.

It has been recalled that Einthoven himself told the story that one of the earliest electrocardiograms that he took was of one of his colleagues whom he had induced to stay late at the Laboratory for experimental purposes. This record showed some unexpected variation in wave shape which Einthoven analysed from first principles (this was long before he had done any systematic work on the wave form of electrocardiograms from abnormal subjects). As a result he gently suggested that the subject should visit his physician and in the meantime suggested to the physician, that he should look for a formerly unrecognised abnormality. This was done and Einthoven's prediction was fully confirmed although the physician stated that without the insistent suggestion, based on the early electrocardiogram, the condition would almost certainly have remained unrecognised.

Einthoven in his conversation and writing used impeccable English and was once asked how, since he rarely travelled, he had obtained such mastery. His reply was that it was his custom throughout his life to read a chapter of a book from an English writer of repute each night before going to sleep so that he became as familiar with English idiom as he was with his own.

Einthoven for many years had a high blood pressure which caused him some concern and he always had a blood pressure check once each month. This fact was never evident in his behaviour or appearance and was unsuspected by his contemporaries. There is no record that he ever had an electrocardiogram taken and in this he was not unlike many cardiological physicians of later times. Strangely, his anxiety was unfounded as neither his blood pressure nor his heart were responsible for his ultimate decease. He died of carcinoma.

He was the recipient of world wide scientific honours which were crowned in 1924 when he received the Nobel prize for physiology to mark his epoch-making work in the design and establishment of the electrocardiograph. He died in 1927.

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APPENDIX

The following is a list of institutions and doctors to whom Cambridge (England) Electrocardiographs were supplied *before the close of* 1915. It indicates the world-wide interest and many of the names will be recognised as pioneers in electrocardiography. The list is as nearly in date order as it is possible now to determine.

The University College Hospital, London. (Sir Thomas Lewis).
St. Bartholomew's Hospital, London.
Guy's Hospital, London. (Sir Herbert French).
London Hospital Medical College, London. (Sir James MacKenzie).
Dr. Thomas Lewis, London.
The Pathological Laboratory, University of Cambridge. (Sir G. Sims Woodhead).
Dr. Michell, Cambridge.
Royal Infirmary, Liverpool. (Dr. J. Hay).
Dr. J. Hay, Liverpool.
The School of Medicine, University of Leeds. (Dr. Wardrop Griffiths).

The Royal Infirmary, Edinburgh. (Sir Sharpey Schafer).
The University College, Dundee.
Sir William Osler, Regius Professor of Medicine, University of Oxford.
The Physiological Department, University of Lyons, France.
The Marey Institute, Boulogne-sur-Seine.
Dr. Louis Gallavardin, Lyons Hospital, France.
The Physiological Laboratory, (Prof. Einthoven), Leyden University, Holland.
Physiological Laboratory, Royal University, Groningen, Holland.
Dr. Avery Newton, Bad Nauheim, Germany.
Pathological Laboratory, University of Naples.

Government General Hospital, Madras, India.
Dacca College, Dacca, India.
Dr. M. D. D. Gilder, Taj Building, Hornby Road Fort, Bombay, India.
The Post Graduate Medical School and Hospital, New York, U.S.A.
The Nutrition Laboratory, Carnegie Institution, Washington, U.S.A.
The Physiological Department, University of Nebraska, U.S.A.
The College of Medicine, University of Syracuse, U.S.A.
The Physiological and Pharmacological Departments, University of Minnesota, U.S.A.
The Department of Physiology, Harvard Medical School, Boston, Mass,. U.S.A.
Peter Bent Brigham Hospital, Boston, Mass., U.S.A.

The University of California Hospital, San Francisco, U.S.A.
Stanford University, San Francisco, U.S.A.
The University of Toronto, Canada.
St. Thomas's Hospital, London.
Royal Hospital for Diseases of the Chest, London. (Sir Arnold Stott).
The Middlesex Hospital, London.
Guy's Hospital, London, (Pathological Department).
The National Hospital for Diseases of the Heart, London.
The Mount Vernon Hospital, London.
Dr. F. W. Price, London.

Dr. A. W. Stott, London.
Dr. Strickland Goodall, London.
Dr. Herbert French, London.
Sheffield Royal Hospital, Sheffield.
David Lewis Northern Hospital, Liverpool.
Ancoats Hospital, Manchester.

Royal Victoria Infirmary, Newcastle-upon-Tyne.
Royal Infirmary, Glasgow.
Dr. John Cowan, Glasgow.
Royal Victoria Hospital, Belfast. (Dr. M'Ilwaine).

Dr. M'Ilwaine, Belfast.
Hospital de la Pitie, Paris.
Dr. R. Moulinier, Bordeaux, France.
Dr. Albert Fraenkel, Badenweiler, Germany.
Laboratoire de Psychologie, Universitie de Geneve, Switzerland.
Institut de Physiologie, Universite de Liege.
Hopital Saint Pierre, Brussels.
Royal Hospital, Copenhagen.
Ill. Clinica Medica, University of Naples.
Physiologisches Kabinett, Landwirtschaftliches Institut, Moscow.

Physiologische Laboratorium, Wissenschaftlicher Verein, Warsaw.
Instituto di Clinica, Medica, University of Genoa.
Dr. Vlad Danulescu, Bucarest, Roumania.
College of Physicians and Surgeons, Columbia University, New York.
Drs. Mayo, Graham, Plummer, and Judge, New York.
Dr. Selian Neuhof, New York.
Bellvue Hospital, New York.
Dr. Herrick, Chicago, Ill., U.S.A.
Department of Medicine, University of Pittsburg, Pa., U.S.A.
Presbyterian Hospital, Philadelphia, Pa., U.S.A.

The Stanford University, San Francisco, U.S.A.
Dr. A. T. Fulton, Brown University, Providence, R.I., U.S.A.
Clifton Springs Sanitarium, U.S.A.
University of Indiana, U.S.A.
Physiol. Lab., Western Reserve University, Cleveland, Ohio, U.S.A.
Massachusetts General Hospital, Boston, Mass., U.S.A.
St. Michael's Hospital, Toronto, Canada.
Drs. Dwyer and Loudon, Toronto, Canada.
Montreal General Hospital, Montreal, Canada.
Physiological Dept., McGill University, Montreal, Canada.

The Royal Victoria Hospital, Montreal, Canada.
Winnipeg General Hospital, Winnipeg, Canada.
Dr. E. Newton Drier, Vancouver, B.C., Canada.
Physiological Laboratory, Grant Medical College, Bombay, India.
Dr. Hume Turnbull, Melbourne, Australia.
Dr. Silberberg, Melbourne, Australia.
Physiological Institute, University of Sendai, Japan.

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